FINAL REPORT

CLASSIFICATION OF THE COASTAL ENVIRONMENTS OF THE WORLD

Bruce Hayden
Robert Dolan

Department of Environmental Sciences
University of Virginia

FEBRUARY 1975

OFFICE OF NAVAL RESEARCH
GEOGRAPHY PROGRAMS

Nonr-N00014-69-A-0060-0006 • Task No. NR389-158

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ACKNOWLEDGMENTS

This work was performed under Contract No. Nonr N00014-69-A-0060-0006, Task Order No. NR389-158 of the Office of Naval Research Geography Programs with the Department of Environmental Sciences, University of Virginia.

The list of appropriate acknowledgments resulting from four years of research is necessarily a long one. To reduce this expression of gratitude to a minimum, we reiterate our thanks to those acknowledged in each of the eleven technical reports issued under this contract; however, special recognition is due in a number of cases. First we offer special thanks to Ms. Mary Vincent who served in an outstanding manner in numerous capacities but most specifically as a data-acquisition administrator. Without her unique skills in this area, progress could not have been as rapid as it has been. Special recognition is also due Mrs. Wilma Le Van and Mrs. Mary-Scott Marston whose dedication always exceeded expectations and Mr. James Carswell, whose efforts in illustration and publication of our reports have proved invaluable. The intellectual and technical skills contributed by Dr. Linwood Vincent and Dr. Donald Resio also deserve restatement here.

Special thanks to Drs. G. Hornberger, J. Zieman, and J. Fisher for their analytical skills and to our staff: Wilson Felder, Jeff Heywood, Ken Bosserman, Kate Kendall, Doug Lloyd, Nancy Morbeck, Steve Piccolo, Karen Aprill, Ruth Kampuries, Mary Nelson, Mia Slattery, Marsha Toney, Laura Wallace, and Betsy Byrd.

Finally, we thank the staff of the Coastal Studies Institute of Louisiana State University for the good services and cooperation afforded us.

ABSTRACT

This final report summarizes the products of more than four years of research in the classification of coastal environments and includes three manuscripts detailing the results and conclusions of three studies not issued in technical report form. The three studies included are titled "Coastal Wave Climates of the Americas," "Coastal Marine Fauna and Marine Climates of the Americas," and "An Assessment of Remote Sensing as a Tool in Classifying Coastal Landscape Elements."

In addition, an evaluation of data quality, quantity, availability, and suitability for the purposes of classifying coastal environments is included. Also contained within this report are statements as to the kinds of expertise required to accomplish the research conducted and the expertise generated during the investigation.

We have concluded that the coastal environment may adequately be classified into a series of natural environmental complexes which recur in disparate geographical locations when the dominant processes shaping the environment are similar in quality and magnitude and that within these complexes assumptions of homogeneity of environmental attributes are appropriate at the analysis scales used. It is proposed that the natural complexes of the coastal environment could serve as geographic units in future information systems for the coastal environments.

INTRODUCTION

The research project Classification of the Coastal Environments of the World conducted at the University of Virginia in the Department of Environmental Sciences under ONR Geography Programs Contract No. N00014-69-A-0060-0006, initiated in 1971, is now complete. Its objective, stated in our first research proposal, was to answer the question: "Are there natural complexes of coastal environments that are duplicated around the world when the processes forcing functions are similar?" We have answered this question in the affirmative and have reported our findings in a series of eleven technical reports. Included in this Final Report for Contract No. N00014-69-A-0060-0006 is a summarization of our research and the disclosure of research findings not contained within the issued technical reports or publications.

In essence our research task was to systematize coastal information throughout the classification process. The resultant classes of coastal environments could then serve as the basis for structuring information systems thereby circumventing the problems inherent in data-storage systems. Advancements in information-systems science consequently was the focus area of Naval application. It would be an overstatement to say that we have produced an information system ready for operationalization by the Navy and application to Navy needs. It is more appropriate to state that the classification system we developed provides natural units of the coast within which statistical summarizations of coastal information may be generally applied. This reduces the necessity of storing all data collected for the coastal unit. Additionally, coastal units of the same class for which information is deficient may be inferred to have similar statistical attributes.

Although this is a significant distance from an operational information system, it illustrates the essential difference between a data-storage system and an information system. That is, an information system should provide information freed from the constraints of the specific spatial and temporal coordinates of the original collection of primary data. The problems of how to generalize data and extend its applicability beyond the spatial and temporal constraints of the primary data collection, and how to evolve from a data-storage system to an information system are one and the same. Once the bounds in space and time are defined, raw data may be added to the information system, by summarization, and applied. Much of our effort has focused on the tools needed to accomplish these ends. We have done pioneering work in the application of multivariate statistical procedures to the problem of systematizing coastal information in Technical Report No. 9, *Systematic Variations in Offshore Bathymetry*, Resio *et al.*, 1973; Technical Report No. 10, *Systematic Variations in Inshore Bathymetry*, Hayden *et al.*, 1975; and Technical Report No. 11, *Systematic Variations in Barrier-Island Topography*, Vincent *et al.*, 1975. Information storage economics of 100 fold are consequently now available for certain attributes of the coastal environment.

While we are convinced that substantial progress has been made toward the development of information systems of reasonable proportion, our work as reported in eleven technical reports has resulted in significant contributions to the base of knowledge about our coastal environment.

DESIGN OF THE CLASSIFICATION SYSTEM

The problem of designing a classification system was an intellectual exercise in its initial stages. Prior attempts to systematize coastal information had resulted in a coarse global classification based upon a single element or a local coastal investigation focusing on a single process. We concluded that the coastal environment is the result of a multiplicity of processes within the context of coastal materials. Based upon a survey of the operative processes, we concluded that two directional or orientational aspects of these many processes are generally common. First, recognizable gradients along the coast are clearly evident in the geographical display of the various attributes of the coastal environment. Such along-the-coast distributions are found for atmospheric, marine, and terrestrial attributes. Secondly, there is a pronounced organization of attributes normal to the trend of the coast.

We also concluded that environmental organization along the coast is a macro-scale phenomena and is related to: 1) large scale circulation patterns of the atmosphere; 2) large scale circulation patterns of the oceans; and 3) large scale regional organization of geologic materials and processes. Large scale attributes in turn make possible the conditions within which the smaller scale processes acting normal to the coast are operative. These large scale attributes were then selected as the defining attributes of the first level of our classification. At this first level of classification the essential question is "What is there in terms of both materials and processes?" Thus the first level of classification of the coastal environment as organized along the coast, referred to in our technical literature as the $\hat{\ell}$-system, consists of three defining criteria classified independently: 1) the atmospheric climate; 2) the marine climate; and 3) the terrestrial interface of land, sea, and air. Each of the three components may stand alone as a separate classification system or be united as a single three-part environmental classification of the coast. The details of this classification as applied to the coasts of the Americas is presented in Technical Report No. 1, *Classification of the Coastal Environments of the World: Part I, The Americas*, Dolan *et al.*, 1972. The classification system was subsequently applied to the coasts of Africa and reported in Technical Report No. 3, *Classification of the Coastal Environments of the World, Part II, Africa*, Hayden *et al.*, 1973. The process of classification of coastal environments is detailed in Technical Report No. 2, *Classification of Coastal Environments Procedures and Guidelines*, Dolan and Hayden, 1973. In Technical Report No. 4, *Classification of Coastal Environments Procedures and Guidelines A Case Study*, Dolan *et al.*, 1973, illustrates the $\hat{\ell}$-system of classification using the east coast of the United States as a case study.

The problem of classifying the coastal environment as organized across the coast (the $\hat{\eta}$-system) proved more difficult. At first we concluded that the multiplicity of processes acting normal to the coast should, when the magnitude of the processes are similar, give rise to a sequence of subzone widths (normal to the coast) that would be definitive; i.e., provide a recognizable class or type of coastal environment. Consequently we defined a subset of six subzones of the coastal zone, measured their widths along barrier-island interfaces of the Atlantic and Gulf coasts of the United States, and analyzed these six widths as a vector using eigenvector analysis. We reported the results of this analysis in Technical Report No. 5, *Classification of Coastal Environments: Analysis Across the Coast, Barrier Island Interfaces*, Resio *et al.*, 1973. Although seven definable groupings or classes were found, some of which had multiple occurrences, they represented an excessive weighting of the relatively stable deep-water and the inland terrestrial zones: Since the subaqueous and subaerial beach zones played little role in defining the classes, the width of these six zones was rejected as the appropriate defining attribute for the classification.

After considerable deliberation we decided that topographic attributes of each of the six zones would be a more appropriate measure reflecting the formative processes to a higher degree. Consequently three studies were initiated to assess the characteristic morphologic organizations of the coastal zone. The first study dealt with offshore bathymetry from the shoreline to a distance 9 miles (14 km) offshore. Transect data was extracted from hydrographic charts and analyzed using multivariate statistics. Three new variables characterized 97% of the topographic variance in offshore bathymetry and the magnitude of these new variables varied systematically along the coast. The results of this study were reported in Technical Report No. 9, *Systematic Variations in Offshore Bathymetry*, Resio *et al.*, 1974. Similar studies of the inshore bathymetry (from the shoreline to 1200 ft [365 m] offshore) and barrier-island topography were conducted and reported in Technical Report No. 10, *Systematic Variations in Inshore Bathymetry*, Hayden *et al.*, 1975, and Technical Report No. 11, *Systematic Variations in Barrier-Island Topography*, Vincent *et al.*, 1975.

Based on the study of offshore and inshore bathymetric organization and barrier-island topography, we concluded that the topographic attributes of the coastal subzones are appropriate to use to further stratify the environmental types defined in the $\hat{\ell}$-system of classification. We also showed that eigenvector analysis of the topographic attributes is an ideal and objective procedure for the classification of environmental organization across the coast.

Auxiliary Studies

Several auxiliary studies were conducted which contributed to our efforts to classify coastal environments. Three of these studies were released as technical reports:

1) Technical Report No. 6, *Classification of the Coastal Environments of the World The Climatic Regimes of Western South America: A Case Study*, Biscoe *et al.*, 1973. In this report inherent differences in the climatic regimes along the west coasts of North and South America are examined in detail. Portions of the research reported here served the research requirement for the degree of Master of Science awarded to Mr. Carlton Biscoe, Jr.

2) Technical Report No. 7, *Quantification of Shoreline Meandering*, Vincent, 1973. In this report meandering of the Cape Hatteras barrier-island shoreline is quantified. The work met the research requirements for the Ph.D. degree awarded Dr. Linwood Vincent by the University of Virginia.

3) Technical Report No. 8, *An Integrated Model of Storm-Generated Waves*, Resio and Hayden, 1973. This report, which served as the research requirement for Dr. Donald Resio's Ph.D., examines in detail the probabilistic linkage between mid-Atlantic wave and surge climates and the nature of the atmospheric circulation.

In addition to Technical Report Nos. 6, 7, and 8 three other studies were conducted the results of which were not released in technical report form. Manuscripts for each of these studies are presented in Appendices A, B, and C of this Final Report in keeping with the full disclosure clause of our contract and in keeping with the concept that the technical-report reader community will gain from our findings. Portions of these studies will appear in print at a later date; however we hope the preliminary manuscripts may serve in the interim.

DATA AVAILABILITY FOR COASTAL-ENVIRONMENTS CLASSIFICATION

At the outset of our investigations we expressed the belief that the data base to accomplish the proposed task existed and that a primary data-acquisition program was not required or requested. Although there were always deficiencies of available data we did find sufficient data and our task was completed. We studied the coastal environments of North America, South America, and Africa.

An assessment, based upon our experiences, of the suitability of environmental information in eight broad classes for North America, South America, Central America, and Africa is presented in Table 1. This assessment provides a perspective of data availability and quality differences by subject matter, class, and geographic locus even though it is subjective.

In general the existence of needed data posed few problems when compared with the logistical and data-reduction problems. The nature of these problems are summarized in tabular form in Table 2. The major acquisition problems resulted from 1) foreign sources, 2) the lack of a central deposition of some data collections and, 3) the time-consuming task of extracting and collecting data published in previous literature. The man-hours required to find data sources and initiate the acquisition process were considerable. As a rule it may be said that the costs of amassing data for such a research effort varies directly with the area density of data required.

A detailed assessment of the utility of remote sensing as a data base for classifying coastal environments is presented in Appendix C.

TABLE 1

Data Suitability

	Atmospheric	Geologic	Marine	Biologic	Offshore Bathymetry	Inshore Bathymetry	Barrier-Island Topography	Wave Climate
NORTH AMERICA								
Geographic Coverage	A	A	B	B	A	B	A	B
Data Density or Map Scale	A	B	C	B	A	B	B	C
Temporal Coverage	A	E	C	E	E	D	D	C
Previously Summarized or Classified	C	B	C	C	D	E	E	C
CENTRAL & SOUTH AMERICA								
Geographic Coverage	A	A	B	C	NOT INCLUDED IN STUDY			
Data Density or Map Scale	A	C	C	C				
Temporal Coverage	D	E	D	E				
Previously Summarized or Classified	C	B	C	C				
AFRICA								
Geographic Coverage	A	A	B	C	NOT INCLUDED IN STUDY			
Data Density or Map Scale	A	C	C	C				
Temporal Coverage	D	E	D	E				
Previously Summarized or Classified	C	B	C	C				

A) Good
B) Adequate
C) Marginal
D) Poor
E) Non-Existent

TABLE 2

Summary of Data Logistics

Data Category	
Atmospheric	
Pressure (N. Hemisphere)	I.A.3.i.
Weather Maps	III.B.3.i.
Wind Fields	III.B.3.i.
Cloud Cover	III.D.4.i.
Rainfall & Temperature	III.E.4.i.
Marine	
Temperature	III.B.4.i.
Salinity	III.B.4.i.
Currents	III.B.4.i.
Waves	III.B.3.i.
	I.A.3.ii.
Offshore Bathymetry	III.B.2.i.
Inshore Bathymetry	II.F.2.iii.
Geologic	
Lithology (North America)	III.B.4.i.
Lithology (Foreign)	IV.B.4.iii.
Topography	III.B.4.i.
	III.B.2.i.
Biologic	
Terrestrial Vegetation	III.G.4.i.
	III.H.2.iii.
Marine Fauna	III.H.2.iii.
	III.G.4.i.

Data Source
I. Single Federal office
II. Numerous Federal offices (regional)
III. Publications including Federal

Data Form Available
A. Machine processable form
B. Map form
C. Original data sheets and charts
D. Photography (including satellite images)
E. Statistically summarized data (tabular)
F. Plotted profiles
G. Previous classifications (map display)
H. Published in journals, monographs or books

Data Reduction Required
1. None required
2. Put in machine processable form
3. Statistically summarize
4. Remap or plot

Time Required to Obtain the Data
i. Less than 1 month
ii. 1 to 4 months
iii. More than 4 months

DATA SOURCES

Great quantities of data were required to systematize and classify coastal information. The difficulty in acquiring this data was compounded by the diversity of data types required and their numerous sources. Although there is no central clearing house for coastal information, numerous Federal agencies and several private firms publish catalogs of available information. Our efforts to acquire coastal information could have been abbreviated considerably had we known about these catalogs at the outset of our investigation. The construction of a bibliography of such catalogs constitutes a product of our research. It is hoped that this tabulation will serve subsequent investigations.

Catalogs of Available Data

A. Meteorological and Climatic Data

1. Catalogue of Meteorological Data for Research
   Part I, II, III
   Secretariat of the World Meteorological Organization
   Geneva, Switzerland

2. Catalog of Meteorological Satellite Data
   Television Cloud Photography
   Tiros, Essa and Itos Catalog No. 5.31 through 5.327
   NOAA
   Washington, D.C. 20402

3. ATS Meteorological Data Catalog
   for the Applications Technology Satellite
   Volume I 7 December 1966 - 1 April 1969
   Volume 2-5 1 August 1969 - 25 May 1970
   ATS Project Manager
   Goddard Space Flight Center
   Greenbelt, Maryland

4. Nimbus II HRIR Montage Catalog
   Nimbus II, User's Guide
   Nimbus II, Data Catalog, Vol. 1-5, Data Orbits 1035-2458
   Nimbus III, " " Vol. 1-6, " " 109-5529
   Nimbus IV, " " Vol. 1-3, " " 131-1956
   Goddard Space Flight Center
   Greenbelt, Maryland

B. Marine Data

1. Catalog of Nautical Charts and Publications

   Sections:

   Miscellaneous Charts & Sheets (N.O. Pub. #1-N-B)
   Special Purpose Navigational Charts & Publications
   (N.O. Pub. #1-N-A)
   Numerical Listing of Charts (N.O. Pub. #1-N-L)
   Catalog of Classified Charts (restricted sale)

   Regions: 0 United States
   1 Canada, Greenland & Iceland
   2 Central & South America & Antarctica
   3 Western Europe
   4 Scandinavia, Baltic & USSR
   5 Western Africa & Mediterranean
   6 Indian Ocean
   7 Australia & Indonesia
   8 Oceania
   9 East Asia

   U.S. Oceanographic Office
   Washington, D.C.

2. Coastal & Geodetic Survey Nautical Charts
   Exclusive U.S. coastline
   1:24,000; 1:62,000; 1:250,00
   Published jointly under
   U.S. Naval Oceanographic Office
   Washington, D.C.

3. Atlas of Pilot Charts
   South Pacific and Indian Ocean
   Central American Waters, South Atlantic Ocean
   U.S. Naval Oceanography Office
   Washington, D.C. 20402

4. Catalogue of Publications
   Sailing Directions in Volumes and
   other Hydrographic Publications
   Defense Mapping Agency
   Washington, D.C.
   and any state map agent

5. User's Guide to NODC's Data Services
   Key to Oceanographic Records Documentation #1
   National Oceanographic Data Center
   Washington, D.C.

6. Catalogue of Accessioned Publications
   World Data Center A
   Oceanography
   Rockville, Maryland   20852

C. Topographic Data

1. Map Supply System Catalog
   Asia, Australia, & the Pacific
     Vol. 1 Asia Mainland
     Vol. 2 Australia & Islands of Pacific
     (both volumes are 1:60,000 & larger)
   Western Hemisphere (1:60,000 & larger)
   Europe, Africa & Middle East (1:60,000 & larger)
   World small scale (smaller than 1:60,000)
   Dept. of Army, Corps of Engineers
   U.S. Army Topographic Command
   Washington, D.C. 20315

2. USGS Topographic Series
   Exclusive of U.S. coastline
   State index maps available in 1:24,000;
   1:62,000; 1:250,000
   USGS
   1200 S. Eads Street
   Arlington, Va. 22202

3. List of Published Soil Surveys
   U.S. Dept. of Agriculture
   Soil Conservation Service
   Information Division
   Washington, D.C. 20250

4. Map Depository Catalog
   Telberg Book Corp.
   P.O. Box 545
   Sag Harbor, N.Y. 11963

5. Profiles of Inshore Bathymetry
   Loose copies of different locations on the
   Eastern & Gulf coasts
   CERC
   Kingman Bldg.
   Ft. Belvoir, Va. 22060
   and Regional Offices of Army Corp. of Engineers

6. Index to Canadian Topographical Maps
   Exclusive to Canada available in 1:50,000; 1:250,000
   Map Distribution Office
   Surveys & Mapping Brancy
   Dept. of Energy, Mines & Resources
   Ottawa, Canada

D. Atlas Data

1. Bibliography on Marine Atlases
   American Meteorological Society
   Meteorological & Geoastrophysical Abstracts
   National Oceanographic Data Center
   Washington, D.C.

2. International Maps & Atlases in print
   edited by Kenneth L. Winch
   R.R. Bowker Inc.
   New York, N.Y.

E. Aerial Photography Sources and Types

1. Agricultural Stabilization & Conservation Service
   Dept. of Agriculture
   2505 Parleys Way
   Salt Lake City, Utah 84109
   (For N. Dakota, Nebraska, Kansas, Arkansas, Louisiana, & States to the west)
   Inland by county

2. Agricultural Stabilization & Conservation Service
   Dept. of Agriculture
   45 S. French Broad Avenue
   Asheville, N. Carolina 28801
   (For all other states)
   Inland by county

3. American Air Surveys, Inc.
   907 Pennsylvania Avenue
   Pittsburgh, Pa. 15222
   Commercial

4. Bureau of Land Management
   Dept. of the Interior
   Washington, D.C. 20240

5. Carto-Photo Corp.
   520 Conger St.
   Eugene, Oregon 97402

6. Cartographic Archives Division
   National Archives (GSA)
   Washington, D.C. 20408
   Historical photography prior to 1940

7. Chesapeake Bay Ecological Program Office
   Bldg. E 105
   NASA - Wallops
   Wallops Station, Va. 23337
   Chesapeake Bay and Mid-Atlantic coast

8. Coastal Engineering Research Center (CERC)
   Kingman Bldg.
   Ft. Belvoir, Va. 22060
   Index of available aerial photography in U.S.

9. EROS Data Center
   Sioux Falls, South Dakota 57198
   Skylab, ERTS, NASA photography

10. Forest Service
    Dept. of Agriculture
    Washington, D.C. 20250
    Inland

11. Coastal Mapping Division, C3415
    National Ocean Survey, NOAA
    Rockville, Maryland 20352
    Coastal to present

12. Soil Conservation Service
    Dept. of Agriculture
    East-West Highway & Belcrest Rd.
    Hyattsville, Md. 20781

13. United States Geological Survey (USGS)
    Map Information Office
    Reston, Va. 22092
    Primarily inland with indexes available

14. Virginia Dept. of Highways
    Location & Design Engineer
    1401 E. Broad St.
    Richmond, Va. 23219
    County

E. General Information

1. A Directory of Information Resources in the U.S.
   Federal Government
   With a supplement of Government-Sponsored Information
   Resources
   Natl. Referral Center for Science & Technology
   Library of Congress
   Washington, D.C. 20540

PROJECT STAFF

Classifying coastal environments required a wide sense of professional skills in the physical and mathematical sciences and a support staff commensurate with these skills and the quality of our reports. The following is a list of our staff and their field of expertise which we used to fulfill our research commitments.

Principal Investigators

R. Dolan	Coastal Processes, Field Studies	1971-1975
B. Hayden	Climatology, Ecology, Meteorology	1971-1975

Co-Investigators

G. Hornberger	Hydrology, Hydrodynamics	1971
J. Zieman	Marine Ecology	1971-1972
J. Fisher	Shallow-Water Oceanography Coastal Processes	1973

Research Associates

M. Vincent	Remote Sensing, Data Management	1971-1974
L. Vincent	Coastal Processes (Statistics)	1971-1974
D. Resio	Climatology, Coastal Processes (Statistics)	1971-1974
C. Biscoe	Climatology	1972-1973

Research Assistants

J. Heywood	Remote Sensing	1974-1975
R. Glassen	Coastal Geomorphology	1972-1973
P. Daniels	Geology	1972
K. Bosserman	Wave Climate	1971-1974
N. Morbeck	Cartography	1972
K. Kendall	Data Reduction	1973-1974
E. Gilmore	Data Collection	1971-1972
K. Aprill	Data Collection	1973-1974
D. Lloyd	Data Reduction	1973
W. Felder	Coastal Processes	1973

LIST OF PRODUCTS RESULTING FROM CONTRACT
No. N00014-69-A-0060-0006

I. Technical Reports

TR1 *Classification of the Coastal Environments of the World: Part I, The Americas.* R. Dolan, B. Hayden, G. Hornberger, J. Zieman, and M. Vincent. Feb., 1972.

TR2 *Classification of Coastal Environments Procedures and Guidelines.* R. Dolan and B. Hayden. Feb., 1973.

TR3 *Classification of the Coastal Environments of the World, Part II, Africa.* B. Hayden, M. Vincent, D. Resio, C. Biscoe, and R. Dolan. Feb., 1973.

TR4 *Classification of Coastal Environments Procedures and Guidelines A Case Study.* R. Dolan, B. Hayden, J. Fisher, M. Vincent, L. Vincent, D. Resio, and C. Biscoe. Feb., 1973.

TR5 *Classification of Coastal Environments Analysis Across the Coast Barrier Island Interfaces.* D. Resio, L. Vincent, J. Fisher, B. Hayden, and R. Dolan. Feb., 1973.

TR6 *Classification of the Coastal Environments of the World The Climatic Regimes of Western South America: A Case Study.* C. Biscoe, B. Hayden, and R. Dolan. June, 1973.

TR7 *Quantification of Shoreline Meandering.* L. Vincent. Nov., 1973.

TR8 *An Integrated Model of Storm-Generated Waves.* D. Resio and B. Hayden. Dec., 1973.

TR9 *Systematic Variations in Offshore Bathymetry.* D. Resio, B. Hayden, R. Dolan, and L. Vincent. Nov., 1974.

TR10 *Systematic Variations in Inshore Bathymetry*. B. Hayden, W. Felder, J. Fisher, D. Resio, L. Vincent, R. Dolan. Dec., 1974.

TR11 *Systematic Variations in Barrier-Island Topography*. L. Vincent, R. Dolan, B. Hayden, and D. Resio. Jan., 1975.

II. Auxiliary Studies (Appendices A,B,C)

A. "Coastal Wave Climates of the Americas," R. Dolan and B. Hayden.
B. "Coastal Marine Fauna and Marine Climates of the Americas," B. Hayden and R. Dolan.
C. "An Assessment of Remote Sensing as a Tool in Classifying Coastal Landscape Elements," M. Vincent, J. Heywood, L. Vincent, R. Dolan, and B. Hayden.

III. Journal Articles

1. "Crescentic Coastal Landforms," R. Dolan, L. Vincent, and B. Hayden, published in *Zeitschrift für Geomorphologie*, March, 1974.
2. "Classification of the Coastal Landforms of the Americas," R. Dolan, B. Hayden, and M. Vincent, to be published in *Zeitschrift für Geomorphologie*, April, 1975.
3. "Recent Secular Variations in Mid-Atlantic Winter and Extratropical Storm Climate," D. Resio and B. Hayden, to be published in *Jour. Applied Meteorology*, summer, 1975.
4. "Shoreline Meandering: Hatteras Island, North Carolina," L. Vincent and R. Dolan, to be published in *GSA Bull.*, summer, 1975.

IV. Research Presentations

1. Coastal Dynamics Group Conference
   a. Virginia Beach 1973
   b. Panama City 1974

2. 2nd Shallow-Water Conference
   a. Louisiana State University
   b. University of Delaware

V. Academic

1. Master Degree awarded: Carlton Biscoe, Jr., "Coastal Climates of Chile: Effects of the Subtropical

Anticyclone and Circumpolar Trough," May, 1973. Mr. Biscoe is presently employed under our current ONR contract "Analysis of the Feasibility of a Wave-Climate Calendar."

2. Ph.D. Degrees awarded: Dr. Donald Resio, "An Integrated Model of Storm-Generated Waves," Jan., 1974. Dr. Linwood Vincent, "Quantification of Shoreline Meandering," Aug., 1973. Both Dr. Resio and Dr. Vincent are currently employed by the Army Corps of Engineers at Vicksburg.

3. Ms. Nancy Morbeck: Ms. Morbeck served during the summers of 1971 and 1972 as a student cartographer on this project. She is currently a cartographer for the Newberry Library in Chicago working on the Bicentennial Atlas of Colonial America. She will continue her cartographic studies at the University of Wisconsin beginning in the fall of 1975.

4. Ms. K. Kendall: Ms. Kendall served as our data-reduction specialist in 1973 and 1974. She is currently employed by the National Park Service in the Office of the Chief Scientist.

APPENDIX A

Coastal Wave Climates of the Americas

Bruce Hayden
Robert Dolan

APPENDIX A

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COASTAL WAVE CLIMATES OF THE AMERICAS[1]

ABSTRACT. The geographic distribution of coastal wave environments has to date received little attention. Coastal wave climates of the Americas, when classified according to sea and swell sources and their seasonal variations, agree well with wave-height statistics and there is a marked correspondence with reported distributions of coastal marine fauna. The distribution of wave-climate regimes exhibits hemispheric symmetry with recurring types along both the east and west coasts of the Americas. KEY WORDS: Americas, Climate regimes, Coastal wave climates, Distribution, Hemispheric symmetry.

It has long been recognized that waves and the resultant nearshore currents hold a dominant position in the formation and subsequent modification of coastal landforms. Storm-wave-induced shoreline modifications cause hundreds of millions of dollars in damage each year. Although the dynamics of these wave-shoreline interactions are in part known, quantitative information on wave climates at regional and hemispheric scales is lacking. This deficiency is acutely felt by those responsible for zoning and planning decisions in the coastal areas.[2] Along the east coast of the United States, for example, the Army Corps of Engineers maintains six recording wave gages located in shallow waters where wave modification is pronounced, and thus site-wave environments deviate significantly from the regional wave climates.[3] For other areas of the Americas, the information base is either weaker than along the U.S. east coast, or nonexistent.

This lack of quantitative information creates serious problems to the coastal geomorphologist concerned with the regional distribution of coastal landforms. Because our understanding of the process -response role of waves and currents is largely restricted to a few sites of intensive study, a definitive, comparative study at the present time from a geographic perspective is impossible.[4] Although it is simple to obtain data on factors important to subaerial processes, such as temperature, rainfall, and wind velocity, it is difficult to obtain comparable data on factors important to the subaqueous processes, such as waves and currents. Assessment at hemispheric scales is even more difficult.

Classification of coastal wave climates for wide geographic application has received little attention in scientific literature. The early attempt of Davis, in 1964, focused on the broad latitudinal distribution of gale-force winds and wave climates:[5]

> The greatest stumbling block of all in the development of a morphogenic approach to shorelines is the lack of information concerning the coastal wave regimes which determines not only the nature of wave attack, but also in large part, the strength and direction of coastal currents.

Traditionally, wave climates for specific localities have been constructed from wave observations or hindcasts of waves from meteorological data. Three forms of observational data are available:

1) Visual records made on ships at sea;
2) visual observations made from shore;
3) instrumental wave recorders.[6]

Davis noted that these sources of information taken together were insufficient to develop a clear picture of world wave regimes; nevertheless, several attempts have been made to summarize statistically the observational data.[7]

In 1969, Russell developed a coastal-wave-height classification for South America based on ship records.[8] More recently, Dolan presented a distribution of landward-approaching waves for the Americas according to five significant wave-height categories.[9] Dolan stated that on the west coast of the Americas, the largest waves are in subpolar regions and the smallest waves are in the intertropical zone. In contrast, he noted that along the east coast of the Americas, the highest waves are in midlatitudes, and that in the intertropical zone, the highest waves are found near Panama and Columbia. These hemispherically symmetrical distributions of waves suggest that a wave-climate classification based upon general atmospheric circulation would prove useful.

Because much of the difficulty in classifying wave climates is due to temporal and spatial variability of the wave sources (the windfields), it is essential that this variability be organized and accounted for. Fortunately, meteorologists have confronted this problem in their analysis of the atmosphere according to scales of motion. When considering the generation of waves for classification at hemispheric scales, the planetary and synoptic scales of motion are significant. This paper develops a classification of coastal wave-climate regimes based on the structure of the general atmospheric circulation, and examines the validity of this classification by comparison with available observational wave data.

WAVE ENVIRONMENTS

Small waves generated from local windfields are of limited significance in shoreline processes. The most important waves are those associated with the large, semipermanent wind systems or those associated with migratory storms. These waves take the form of sea if generated near the coast, or swell if generated far from the coast.[10] The problem of understanding coastal wave climates is complicated by the simultaneous arrival at the coast of waves from several different sources. Consequently, the restructuring of wave environments from observational data is very difficult.

Another approach to solving this problem is to hindcast the waves arriving at the shore through analyses of the windfields of individual wave sources.[11]

Although this approach has proven effective and is consistent with observational data, it requires that each site along the coast be hindcasted for each wave-producing event and that the subsequent data be summarized climatically. Time and resources preclude the application of such methods at a hemispheric scale. A deductive approach recommended by Davis involved "using the data of marine meteorology and what is now known of the factors of wave generation and propogation and comparing the conclusions thus reached with the observational record."[12]

CLASSIFICATION MODEL

Planetary Scale

The planetary-scale features of the general atmospheric circulation are semipermanent, spatially and temporally, and include the subpolar low-pressure cells, the subtropical highs, the midlatitude westerlies, and the tropical easterlies. Because these features and their associated surface windfields are well developed over oceanic areas, they provide a ready foundation for the classification of wave-generating winds.

1) The subpolar current;
2) the subtropical current;

3) the intertropical current and;

4) the westerly current.

Of the four major wind-current systems, only the westerly current causes sea and swell in a predominately offshore direction along the coastal areas of the Americas. Therefore, the westerly current is not included in the proposed classification scheme. The dominant directions of coastal swell and the planetary-scale wind currents correspond closely for the east and west coasts of the Americas during both January and July (Figs. 1 and 2).

Near the coastal zone, windstreams associated with major wind currents may be converging or diverging from adjacent windstreams. The attribute of airstream convergence and divergence reflects the prevailing cyclonic (stormy) or anticyclonic (fair weather) curvature of the isobaric field and characterizes various portions within the major wind currents (Fig. 3). This attribute is particularly useful in classifying wave climates for the following reasons:

1) Regions of convergence are generally cyclonic with tight spacing of isobars and with strong winds resulting in high waves;

2) many regions have a strong seasonal character in relation to the direction of wave approach, which is accompanied by a seasonality in convergence and divergence;

3) it was one of the defining attributes of Dolan's classification of coastal climates, thus making the present classification of waves consistent with his climatic classification.

The subpolar wind current along the poleward flank of the subpolar cyclones generates sea and swell affecting the high-latitude continental east coasts. Along the Argentinian east coast, southeast swell from the subpolar current moves toward the equator as near as 20° S latitude. In North America, the land orientation relative to the subpolar low-pressure cell prevents widespread effects of the subpolar current.

The subtropical wind current is associated with the equatorward flanks of the subpolar cyclones and the poleward flanks of the subtropical anticyclones (Fig. 3). The two subtropical current systems, one in the South Pacific, are significant for coastal areas of the Americas. On approach to the west coasts of the

Americas, each system subdivides into three principal currents: a poleward, an equatorial, and a zonal limb.

The poleward limb is directly associated with the adjacent subpolar cyclone, causing cyclonic vorticity and converging airstreams to dominate the adjacent coastal areas. The equatorward limb is associated with the eastern flank of the subtropical anticyclones, causing anticyclonic vorticity and divergence of the airstreams to dominate. The zonal limb is equivalent to the extension to the continent of the main body of the subtropical current. This zonal limb is shown in the swell dominance (maximum) from the west which characterizes the midlatitude sections of the west coast of the Americas.

Although the subtropical currents of the North and South Pacific are similar in form, they differ in seasonal behavior and have important implications for west-coast wave climates. In the Northern Hemisphere during the last week of June, the subtropical anticyclone of the North Pacific moves northward approximately 5° latitude, shifting northward the equatorward and the zonal limbs of the subtropical current and its associated waves.[13] There is no equivalent shift for the subtropical anticyclone of the South Pacific.

In addition, the subpolar cyclone of the North Pacific is relatively stationary with its mean location along the Aleutian Islands or in the Gulf of Alaska.[14] In the Southern Hemisphere, the subpolar low-pressure cells have no preferential geographic position but revolve around the Antarctic continent. The resulting variable in position relative to the Chilean coast results in differences in sea and swell dominance when compared to the North American coast.

The intertropical current consists primarily of the trade-wind systems associated with the equatorial flanks of the subtropical anticyclones in adjacent oceans (Fig. 3). For the east coast of the Americas and its coastal wave climates, the subtropical current of the tropical Atlantic Ocean is significant. Two major branches of the intertropical current are defined: One moves southward along the Brazilian Coast and the other moves into the Caribbean Sea. The Caribbean branch subsequently divides: One branch recurves equatorward, crossing the isthmus of Central America; the other curves into the Gulf of Mexico.

In late June, the strength of the trade-wind system increases abruptly causing the intertropical sea and swell maxima evident in Caribbean coastal areas.[15] Within the intertropical convergence zone, the region between the two subtropical anticyclones of adjacent oceans, eddy disturbances develop into tropical depressions, some of which recurve northward as hurricanes, generating significant sea and swell.

In the midlatitudes of the east coast of the Americas, the dominant airflow is westerly. Characterizing the mid-Atlantic coast of the United States and Argentina's southern coast is the persistence of these midlatitude westerlies which generate swell in the offshore direction along the United States' mid-Atlantic coast and the Argentinian southern coast. The westerly wind system is also a steering current for tropical and extratropical cyclones and is therefore associated with locally heavy seas.

Synoptic Scale

Although the semipermanent atmospheric circulation accounts for much of the large-scale organization of coastal wave climates, migratory cyclones at the synoptic scale give rise to significant departures from these windfields. Three types of migratory cyclones are included in this classification: polar, extratropical, and tropical cyclones.

As used in this study, polar cyclones are cyclonic depressions poleward of the semipermanent, subpolar lows that generally migrate from west to east. Wave generation is restricted to the Arctic Ocean and Bering Sea regions. In these waters, the dominance of pack ice restricts to the summer seasons waves generated by polar cyclones.

Extratropical cyclones are confined to the mid-latitudes within the westerly current and associated with the polar frontal system. Extratropical cyclones generally move from west to east and intensify when moving from land to sea as along the Atlantic Coast and are responsible for the extremes of the wave environment.

Hurricanes are tropical depressions which move from east to west in low latitudes and subsequently recurve poleward and eastward. The gale-force wind velocities which characterize hurricanes generate rough seas; and, in areas devoid of extratropical cyclones, these wind velocities account for the extremes of local wave climates. The low frequency of hurricanes and the widely diverse tracks they follow precludes their dominance in statistical averages for most coastal areas. In the Americas, hurricanes are restricted to the Northern Hemisphere;

their absence in the South Atlantic is attributed to the high levels of shear in the tropical atmosphere over the South Atlantic.[16]

CLASSIFICATION CRITERIA

In this study, wave climates of coastal areas of the Americas were classified according to wave sources for waves dominating the coast. Each class is defined by three attributes:

1) The source of swell;
2) the divergence of airstreams in the coastal zone;
3) the source of sea.

Of the three category classes, the planetary-scale, semipermanent, atmospheric-circulation features and the synoptic-scale, migratory, atmospheric-circulation features denote the actual wave sources (Table I). The remaining category class, divergence of airstreams in the coastal zone, denotes the seasonality of the sea and swell wave environment. A (+) denotes a dominance of divergent airstreams all year; a (-), convergent airstreams all year; and a ($\pm$), divergent airstreams part of the year and convergent airstreams the remainder.

For coasts where swell is largely generated by the large-scale, semipermanent, wind-current systems, the (+) and/or (-) notation denotes the limb of the involved wind current. On coasts where the major component of swell is from migratory cyclones, the (-) notation indicates the convergence associated with cyclonic systems.

A three-part symbolic nomenclature designates the wave-climate regime identified. The first unit of the name refers to the swell source; the second, to the seasonal aspect of the swell; and the third, to the sea source. For example, B±b indicates that:

1) The dominant swell source is the subtropical current (B);
2) the swell source differs seasonally, part of the year under the influence of the divergent (+), equatorward limb of the subtropical current; and the remainder of the year under the convergent (-), poleward limb of the subtropical current;
3) the major sea component originates in migratory, extratropical cyclones (b).

APPLICATION TO THE AMERICAS

Determination of the planetary-scale features was accomplished by the analysis of wave roses for monthly mean swell for each Marsden square adjacent to the coast.[17] The dominant swell directions were compared with monthly mean wind-rose data and maps of monthly mean atmospheric pressure. Each coastal area divided by Marsden squares was assigned one of the four atmospheric wind currents as its swell wave source. For the continental east-coast midlatitudes, characterized by a swell dominance in the offshore direction associated with the westerly wind current, the predominant onshore swell component was selected for analysis. Where these components coincided with the direction of dominant sea, the appropriate synoptic-scale, migratory storm type was assigned as the swell source.

The seasonal attribute of convergence and divergence for the Marsden squares adjacent to the coast was extracted from the coastal-climate-regime classification of Dolan and the appropriate values were assigned.[18] Using the same data set as that for the planetary-scale features, the following procedure was used in the classification of synoptic-scale features:

1) If the dominant direction differed from that of swell, the sea source was classed according to the appropriate synoptic -scale, migratory storm type accounting for that direction;

2) If the dominant sea direction was the same as that of swell and the area was largely devoid of migratory storms, the semipermanent, atmospheric wind-current class assigned to swell for that region was also assigned as the sea source.

The resultant wave-climate regimes are homogeneous for the classes of the defining attributes (Fig.4, Table I): The planetary-scale and synoptic-scale features of the general circulation and the attribute of airstream divergence. Each wave-climate region is assigned a letter-code symbol according to the stratification criteria (Table I).

WEST COAST WAVE CLIMATES

Along the west coast of the Americas, six wave -climate regime types occur. Although a basic symmetry of types B-B, B+B, B$\pm$B, and B-C is evident from pole to

TABLE I.--WAVE-CLIMATE CLASSIFICATION ELEMENTS

Sources of Sea and Swell	Letter Code
I. Large-Scale Semipermanent Wind Currents	
1. Subpolar Current	A
2. Subtropical Current	B
3. Intertropical Current	C
II. Synoptic-Scale Migratory Storms	
1. Polar Cyclones	a
2. Extratropical Cyclones	b
3. Tropical Cyclones	c
III. Wind-Current Divergence (Seasonality)	
1. Divergence All Year	+
2. Convergence All Year	-
3. Seasonally Divergent and Convergent	±

Source: author's own.

equator, two additional types occur: B±b and B∓b. These two types are located along the North Pacific coast of the Americas and result from:

1) Unlike the South Pacific area, large fluctuations in the north-south position of the subtropical anticyclones result in a seasonality of the coastal segments dominated by the convergent and divergent limbs of the subtropical current;
2) migratory extratropical cyclones prevail during the winter season and generate sea significantly greater than that resulting from the semipermanent, subtropical wind current.

Wave-climate type B-B occurs:

1) Along the Chilean southern coast, south of 37° South;
2) along the British Columbian and Southern Alaskan coast (to and) including the Aleutian Islands.

In both locations, storminess and rough seas prevail due to the persistent cyclonic curvatures of the isobaric field and the resultant convergent flow of airstreams near the coast. The dominant sea and swell source in each area is the poleward limb of the subtropical current, and the dominant sea and swell are the same in each area. The percentage of time in which moderate sea (5- to 12-foot-height [1.52 to 3.65 m] class) and moderate swell (6-to 12-foot-height [1.82 to 3.65 m] class) dominate was summarized (Table II). While the source and approach directions of both sea and swell are equivalent in each area, there are several noteworthy differences between hemispheres.

In the Northern Hemisphere, swell has a summer frequency maximum and a winter frequency minimum. Sea, however, is maximum in winter and minimum in summer, marking the absence of a well-developed, subpolar, low-pressure cell in the Gulf of Alaska during the summer months. In the Southern Hemisphere, well-developed, subpolar, low-pressure systems prevail throughout the year; and thus the winter-summer seasonality characteristic of North America is absent, and uniform conditions prevail throughout the year. Another difference between the North American and South American B-B regions is evident. In the Northern Hemisphere, moderate sea dominates approximately 48 percent of the time, moderate swell 28 percent of the time, and the

TABLE II.--DURATION OF 6- TO 12-FOOT (1.82 to 3.65 m) SWELLS AND 5- TO 12-FOOT (1.52 to 3.65 m) SEAS BY SEASON, COAST, AND WAVE-CLIMATE REGIME TYPES

Wave-Climate Regime Type	North America Winter	North America Spring	North America Summer	North America Fall	South America Winter	South America Spring	South America Summer	South America Fall
	Percentage of Time of Sea (Swell)							
West Coast:								
B-B	23(54)	30(50)	31(38)	28(48)	58(26)	55(26)	57(26)	49(30)
B+B	17(33)	17(37)	13(23)	14(23)	52(13)	45(11)	41(7)	48(8)
B±B	6(12)	14(14)	12(10)	6(12)	21(4)	19(3)	17(2)	30(3)
B-C	14(22)	7(14)	14(15)	15(22)	4(10)	4(5)	7(7)	9(11)
B±b	29(47)	33(43)	34(38)	32(39)				
B+b	26(31)	28(38)	25(37)	23(24)				
East Coast:								
A-b	51(30)	48(21)	41(21)	45(35)	47(22)	47(18)	45(21)	45(23)
C±C	51(17)	44(14)	38(7)	43(11)	40(18)	38(14)	33(12)	34(13)
C-C	50(31)	47(24)	47(26)	37(19)				
C±C*	36(23)	40(24)	31(21)	29(15)				
C±c	31(15)	21(8)	15(6)	29(15)				
b-b	32(24)	23(12)	22(10)	33(23)				

*This third occurrence of C±C takes place at the junction of South and Central America.

Source: compiled by author from data in *Oceanographic Atlas of the North Atlantic, Section IV: Sea Swell*, p. 227; *Atlas of the Sea and Swell Charts North Pacific Ocean*, p. 12; *Atlas of Sea and Swell Chart South Pacific*, p. 12.

subpolar lows are fixed in characteristic positions (Table II). In the North Pacific region, the preferential locations of the subpolar lows are in the Gulf of Alaska and the Aleutian Islands; and the close proximity of the coastal area causes sea dominance. In the Southern Hemisphere, the subpolar, low-pressure cells are not fixed in place but rotate around the globe at high latitudes. These cells are therefore adjacent to the coast for a smaller time and swell dominance prevails from the more distant wave generation areas (Table II).

Wave-climate type B+b occurs along the coasts of Washington, Oregon, and Northern California and has no equivalent along the South American west coast. Swell which dominates coastal regions of B+b is generated by the subtropical current and the percentage of swell frequency in the height class, 6-12 feet (1.82-3.65 m), is uniform throughout the year. However, in summer the dominant direction of swell is from the northwest; but, during the remainder of the year, it is from the west. This seasonality shows the change from the dominant, convergent airflow of fall, winter, and spring to the divergent airflow of summer which is a result of the northward shift of the subtropical anticyclone around the end of June.[19] The lack of a similar shift in the subtropical anticyclone of the South Pacific precludes the existence of a similar wave-climate area along the west coast of South America.[20]

Unlike the lack of seasonality in swell, there is a marked seasonality of sea in percentage of wave dominance in the 5- to 12-foot (1.52 to 3.65 m) class due to the occurrence of extratropical storms during the low sun period of the year (Table II). During summer, sea is in the same direction as swell due to a common source and the absence of extratropical storms; in fall, winter, and spring, sea is in a more northerly direction because of migratory, extratropical storms. Although this region (B±b) receives sea from the subtropical current, the sea from migratory storms differentiates this region from B-B to the north and B+b to the south.

Wave-climate type B+b occurs along the southern two-thirds of the Californian coast and is characterized by a prevailing anticyclone curvature of the isobaric field and divergent airflow of the southern limb of subtropical, atmospheric current. The uniformity of the condition throughout the year is due to the uniformity of sea and swell direction (from the

Northwest) and the absence of a marked seasonality of percentage of moderate sea or swell frequency. However, extratropical storms passing to the north add a westerly component to the dominant sea direction during fall and winter storm seasons. The absence of significant migratory, extratropical storms in an equivalent area along the South American west coast precludes this wave-climate class in South America.

Wave-climate type B+B occurs along the west coast of Mexico and along the coasts of Chile and Peru. These areas are dominated in all seasons by anti-cyclonic curvature of the isobaric and divergent flow of airstreams, and the absence of migratory storms. Sea and swell from the northwest dominate all year with a common source of waves of both categories. In both hemispheres, a winter maximum and a summer minimum in percentage of moderate sea- and swell-caused velocities in the wave-generating area characterize each area. However, there are differences in the relative frequencies. Sea is more frequent than swell in North America, and swell is more frequent than sea in South America because of the difference in orientation of the land relative to the wave-generating areas. In the B+B region of Mexico, distant swell-generating areas are shadowed by the land adjacent to the north; no equivalent shadowing occurs in the South American region of B+B.

Although hurricanes and lesser tropical depressions cross Central America and develop off the Central American west coast, the frequency of these events is low and they fail to show up on mean representations of wave frequency and direction statistics.

Wave-climate type B±B occurs along the west coast of Central America and along the coast of Equador. These areas are differentiated by the seasonal occurrence of airstream convergence and the general storminess associated with north-south oscillations of the intertropical convergence zone (intertropical current). The wave-climate regions poleward of these areas are rarely under the influence of these windstreams, and the wave-climate region between these areas is dominated all year by the intertropical convergence. Therefore, the airstreams are convergent during part of the year and divergent during the remainder. Sea and swell in these two areas are caused mainly by the equatorward limb of the subtropical current. However, because a significant component of Southern Hemisphere swell dominates Central America, spring frequency maxima are equivalent to the Equadorian fall frequency maxima (Table II). Unlike the frequency maxima for swell, the frequency maxima for sea for the respective areas are six months apart and reflect the seasonal north-south movement of the intertropical convergence zone.

Wave-climate type B-C occurs along the equatorial west coast of the Americas and is dominated by the convergent-flow streamline from the Atlantic, intertropical, atmospheric wind current. The complexity of directions of approaching waves reflects the atmospheric wave structure of the intertropical convergence zone; however, the high frequency of offshore waves from the northeast associated with the flow across the isthmus of Central America illustrates the uniqueness of this west-coast, wave-climate type. The swell-frequency maximum of summer and fall originates mainly in the Southern Hemisphere; however, the sea maximum of fall and winter is a result of the southward median position of the intertropical convergence zone and the associated local winds (Table II).

East Coast Wave Climates

Along the east coast of the Americas, a basic pole-to-equator symmetry of wave-climate types A-b, C$\pm$C, C-C, and C+C is evident; however, the complex orientations of the North American east coast in relation to wave-generation source regions cause departures from the hemispheric symmetry which is uninterrupted along the South American east coast. These departures are as follows:

1) The land mass of eastern Canada prevents swell from the subpolar current from dominating the east coast of the United States as it dominates the temperate Argentinian coast;
2) the occurrence of hurricanes in the North Atlantic, Caribbean, and Gulf of Mexico has no analog for South America because of a lack of hurricanes in the South Atlantic.

East-coast, wave-climate type A-b occurs along the coast of Argentina and the east coast of Canada. Swell dominating these coastal areas is generated by subpolar currents with dominant directions from the south and the southeast. The year-round presence of subpolar lows around the Antarctic continent and near Greenland precludes a well-defined, seasonal, swell-frequency maxima (Table II). Airflow in the coastal areas is basically convergent, reflecting the frequent tracking of extratropical cyclones across the coast toward polar latitudes. In these areas, sea is primarily the result of these extra-tropical storms, and there is no evidence of a seasonal frequency chiefly because in North America this wave-climate regime does not go as far south as the equivalent Argentinian area.

Wave-climate type C±C occurs along numerous coastal stretches of tropical and subtropical areas of the east coast of the Americas. Both sea and swell arise from the intertropical current and are from the same direction and experience frequency maxima in winter (Table II). Each of these areas is under the influence seasonally of the intertropical convergence zone as it moves northward and southward.

Wave-climate type C-C occurs along the north central zone of South America and along the east coast of Panama. These areas are dominated all year by the intertropical convergence zone. Sea and swell lack the strong seasonality which characterizes the adjacent C±C areas (Table II). Dominant sea and swell directions for these areas are identical, proving that the intertropical current is the common source of waves.

Wave climate type C±c occurs along the coast of the Gulf of Mexico. Because of a lack of hurricanes in the South Atlantic (the major source of significant seas), this type occurs only in the North Atlantic sector. The region is seasonally subdominant with respect to convergence and divergence, with winter being convergent and summer divergent. This aspect of seasonality is evident in swell directions. In winter, north swell from off the coast of North America dominates; and, in summer, southeast swell from intertropical current dominates. This seasonality is evident in the winter sea and swell maxima for this area (Table II).

Wave-climate type b-b occurs along the east coast of the United States and is dominated by sea and swell from extratropical cyclones which cross these coastal areas from the west. It should be noted that the dominant direction of swell is from the west, reflecting the westerly wind current; however, because this component direction does not approach the coast, it is omitted from the classification. Both sea and swell have winter frequency maxima and summer minima; and, although swell statistics include west swell, it is this westerly current which encourages cyclogenesis and steers storms across the coast where they cause shoreward-directed sea and swell. Unlike the equivalent area along the Argentinian coast, this area receives no swell from the subpolar current because of the shadowing effect of the eastern Canadian landmass.

OBSERVATIONAL DATA

The wave-climate classification based upon wave directions and wave sources was tested by comparing its results with two widely differing sets of observational data:

1) The percentage of durations by wave-height classes for shoreward-directed waves;
2) naturally occurring provinces of the coastal marine fauna of the Americas.[21]

Although a functional relationship between wave-climate classes derived through analysis of wave directions and sources and wave-height statistics is not necessarily expected, variation in wind speeds within wave-source types should agree broadly with wave statistics for wave-climate types of multiple occurrence.

Geographers have long relied on the covarying relationship between the structures of the biotic and abiotic aspects of the environment to reinforce and to support the results of classification efforts.[22] Near-shore currents generated by approaching waves result in both vertical and horizontal advections of coastal waters which cause the extant thermal structure of these waters. Since coastal marine fauna are largely limited in their geographic distributions by thermal conditions, it is expected that the distributions of coastal marine fauna should coincide in part with the distributions of coastal wave climates.

Wave Height Statistics

Wave-height statistics for shoreward-directed waves along the coasts of the Americas were summarized by Dolan according to the percentage of time durations for five wave-height classes.[23] Of those wave-climate regime types which occur in both North and South America, all but type C-C have similar wave -height (wave) environments (Table III). Type C-C when near Panama and Columbia has high wave heights; but when it is along the northern coast of South America, it has only moderate wave heights. Therefore, it is clear that wave-climate regime types although located at widely differing sites have similar impinging wave energies. Wave-climate regimes along the northern Gulf of Mexico coast have no equivalent along the coasts of South America. However, wave climates similar both in terms of wave sources and wave-height characteristics would be expected somewhere along the coast of Asia because of the prevailing winds from the inter-tropical current and hurricanes which dominate the wave climate as they do along the northern Gulf of Mexico coast.

Coastal Marine Fauna

Faunal provinces and characteristic distributional extents of coastal marine fauna have been reported by Hedgpeth, Hall, Valentine, Abbott, and Hayden.[24] The transitional locations of coastal marine-faunal

TABLE III.--WAVE-HEIGHT CHARACTERIZATIONS FOR

RECURRING WAVE-CLIMATE TYPES

Wave-Climate Types	North America (10° N to 60° N)	South America (10° N to 60° S)
West Coast:		
B-B	High to very high	High to very high
B+B	Low to high	Moderate to high
B±B	Low	Low
B-C	Low	Low to very low
East Coast:		
A-b	Moderate	Moderate
C±C	Moderate	Moderate
C-C	High	Moderate

Source: author's own from present article and Dolan, Hayden et al., op. cit., footnote 9.

communities were compared with the locations of the boundaries between wave-climate regimes (Table IV). Boundaries within the respective data sets were said to coincide if they were within one degree latitude or an equivalent distance for coasts with an east-west trend. Of the eighteen wave-climate boundary locations, fifteen corresponded to transitional locations of the coastal marine fauna. Of the wave-climate boundaries for which no faunal boundary is reported, two are along the western Caribbean Sea and one is along the southwest coast of Mexico, all are in thermally uniform tropical waters where wave-induced circulations should not result in an altered thermal structure. Although the accuracy of the locations of the faunal and wave -climate boundaries may be questioned based on the original data, the high level of correspondence of the biotic and abiotic data sets is strong evidence in support of these analyses.

DISCUSSION

If observational data on wave environments is to apply to more than specific sites, a definitive means of designating the geographic limits of recording and the recurrences of similar wave environments is necessary. To do this through various means of

TABLE IV.--MARINE FAUNAL TRANSITION ZONES AND BOUNDARIES BETWEEN WAVE-CLIMATE TYPES

Wave-Climate Boundaries		Reported Transition Zones in Coastal Marine Faunal Distributions				
		Hedgpeth	Hall	Valentine	Abbott	Dolan, Hayden et al.
West Coast:						
/B-B	58°N			X		
B-B/B±b	52°N		X	X		X
B±b/B+b	38°N		X	X		X
B+b/B+B	30°N	X	X	X	X	X
B+B/B±B	20°N	X	X	X		X
B±B/B-C	17°N					
B-C/B±B	2°N					X
B±B/B+B	7°S	X				X
B+B/B-B	38°S	X				X
B-B/A-b	56°S					X
East Coast:						
A-b/C±C	28°S	X				
C±C/C-C	1°S					X
C-C/C±C	9°N					X
C±C/C-C	11°N					
C-C/C±C	11°N					
C±C/C±c	22°N					X
C±c/b-b	25°N	X			X	X
b-b/A-b	47°N		X			X

Source: author's own constructed from data in publications of above-named authors, see footnote 24.

classification has been tried before (Table IV). Classification efforts in the natural sciences have traditionally been a stepping stone to more detailed investigation and experimentation and, as such, are vehicles of further research.

Wave climatology as a recognized area of inquiry is in its infancy. The information demands of World War II marked its beginning, and the prevailing trend of coastal erosion in the 1960's and 1970's has created a demand (among natural scientists and managers of coastal areas) for increased information on the nature of coastal wave environments.

FIGURE CAPTIONS--COASTAL WAVE CLIMATES OF THE AMERICAS

Fig. 1. Dominant direction of January swell (small arrows) and the major wave generating atmospheric wind currents: A = subpolar current; B = subtropical current; C = intertropical current; D = westerly current.

Fig. 2. Dominant directions of July swell (small arrows) and the major wave generating atmospheric wind currents: A = subpolar current; B = subtropical current; C = intertropical current; D = westerly current.

Fig. 3. Schematic of the major semipermanent wave generating wind currents associated with atmospheric circulation systems for an idealized distribution of land and sea. Minus signs indicate prevailing convergence of airstreams; plus signs indicate prevailing divergence of airstreams; and a plus-minus indicates seasonally variable convergence and divergence.

Fig. 4. Distribution of wave-climate types for coastal areas of the Americas.

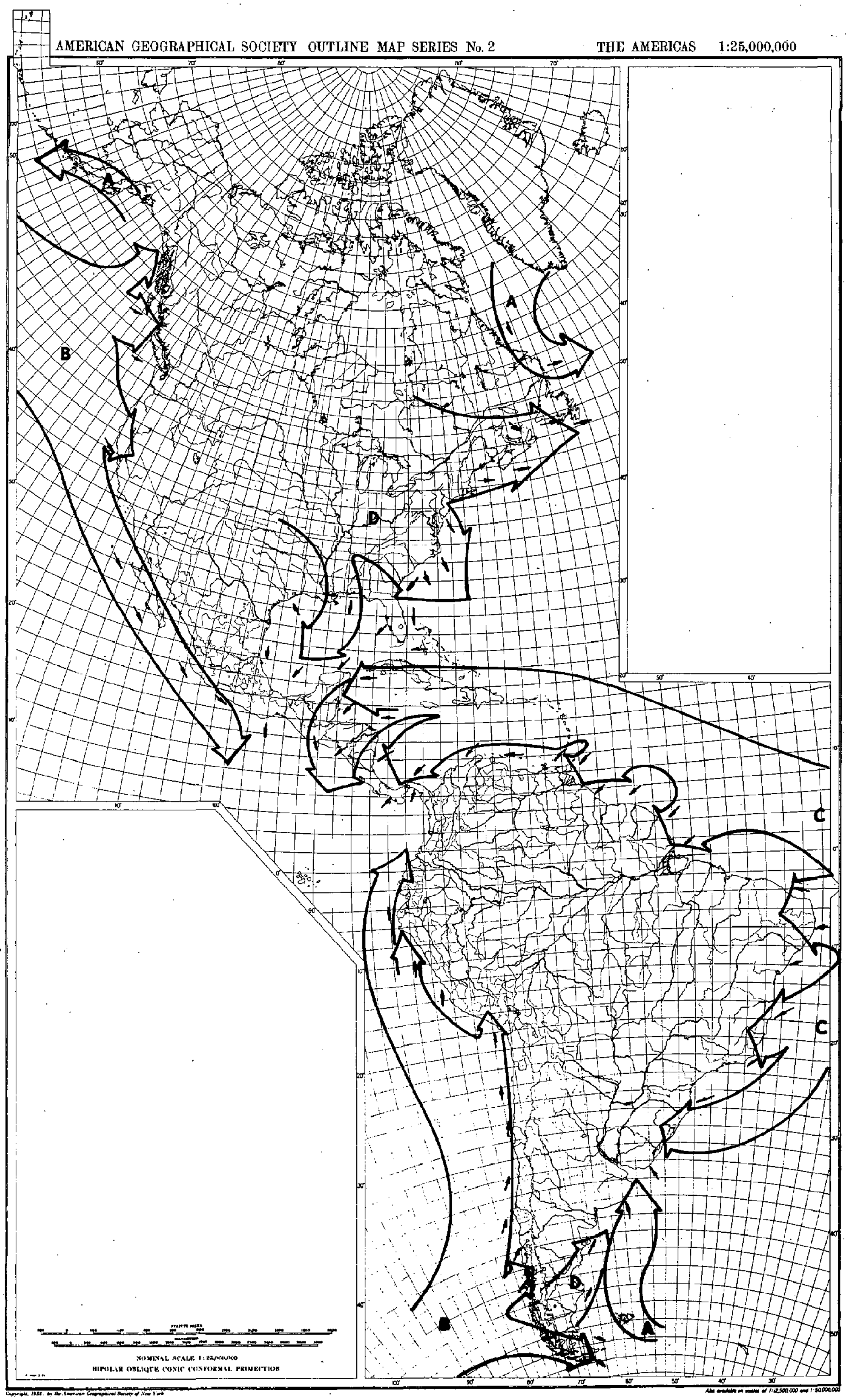

Fig. 1: "Coastal Wave Climates;" first reference on p. 32 of the manuscript.

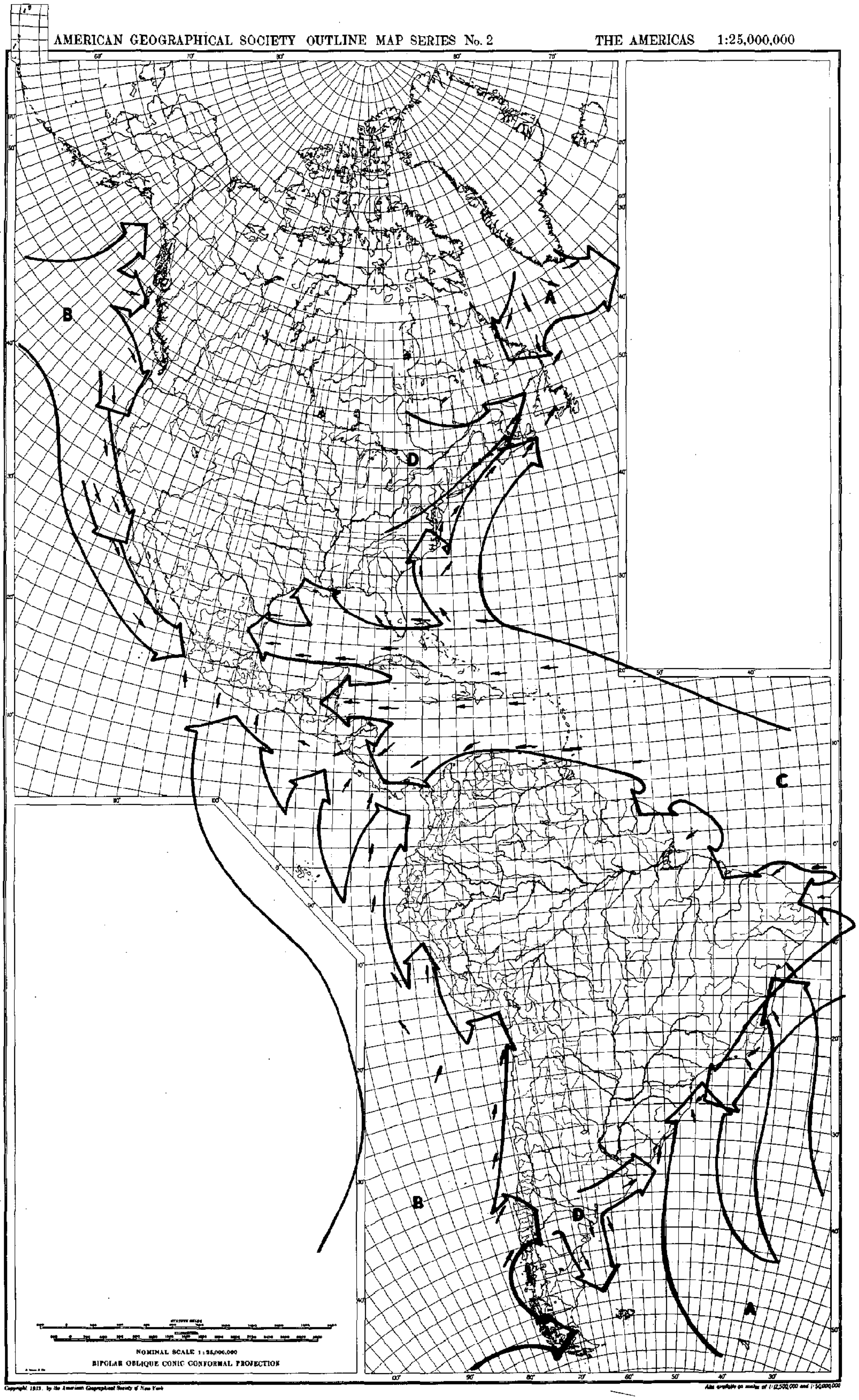

Fig. 2: "Coastal Wave Climates;" first reference on p. 32 of manuscript.

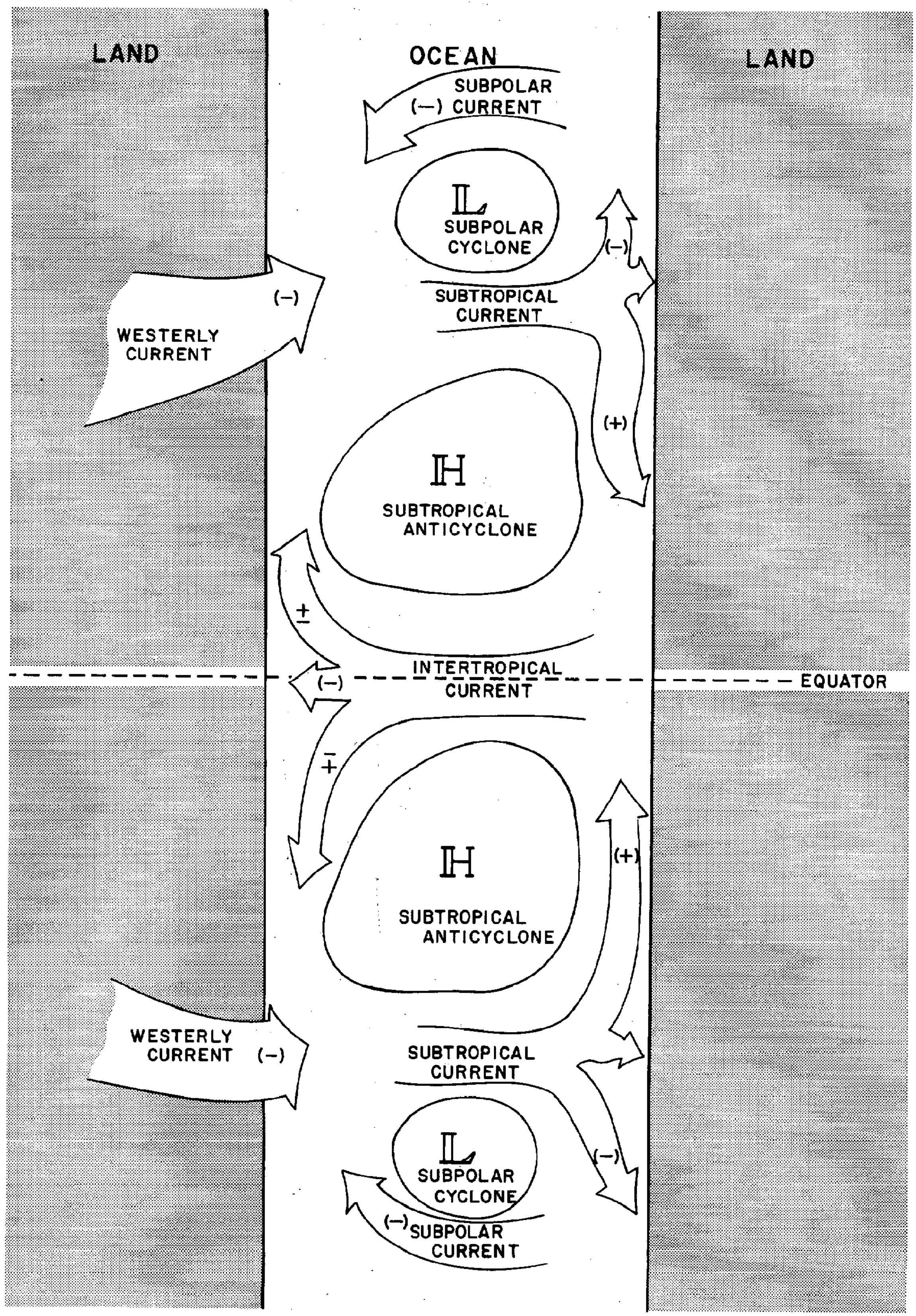

Fig. 3: "Coastal Wave Climates;" first reference on p. 32 of manuscript.

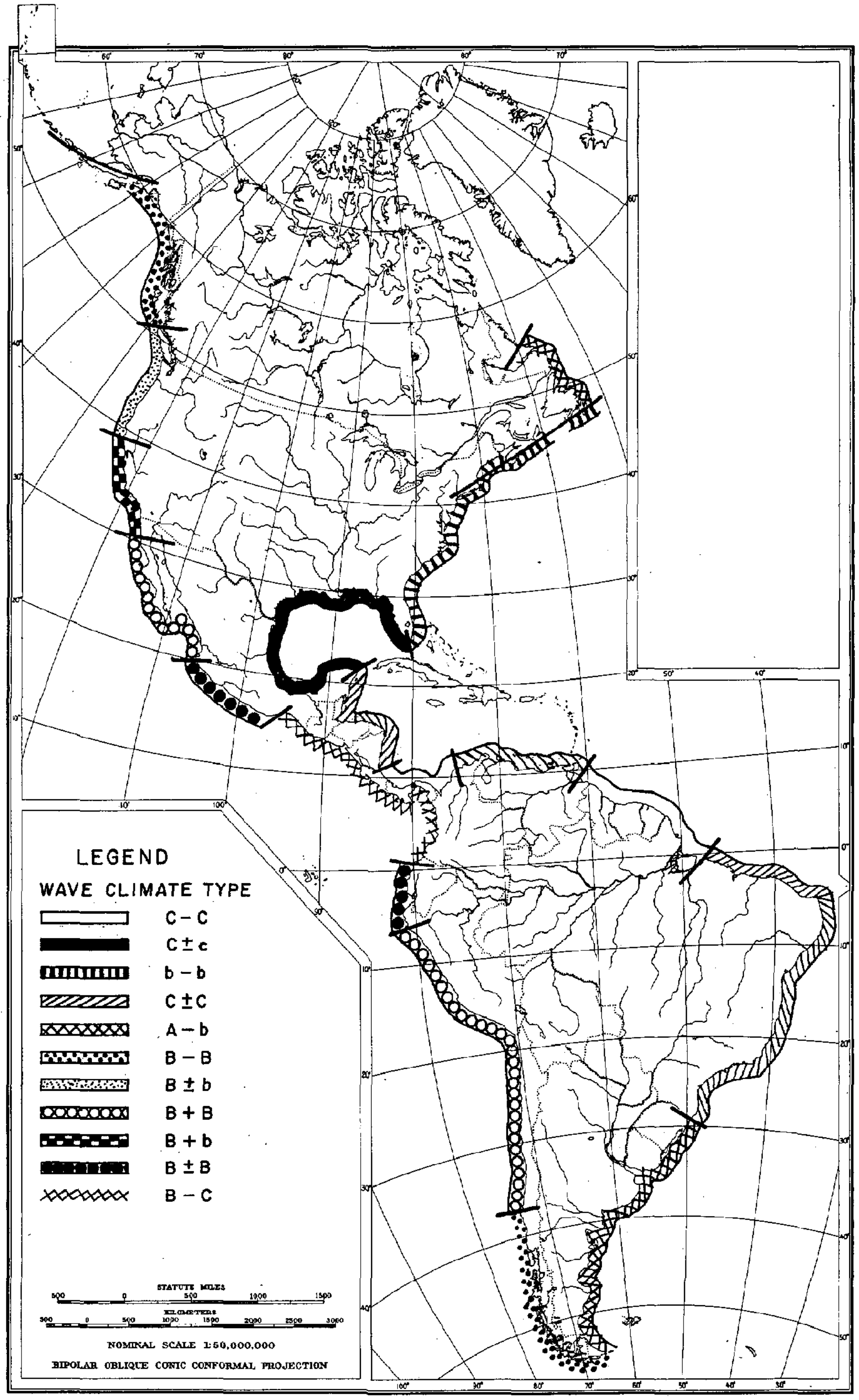

Fig. 4: "Coastal Wave Climates;" first reference on p. 41 of manuscript.

FOOTNOTES--COASTAL WAVE CLIMATES OF THE AMERICAS

1 Research for the study was conducted with a grant from the Office of Naval Research, Geography Programs, University of Virginia, Charlottesville, Virginia 22903.

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3 J. Darling and D. Dumm, <u>The Wave Record Program at CERC</u> (Washington: U. S. Army Coastal Engineering Research Council, 1967); and L. Williams, <u>CERC Wave Gages</u> (Washington: U. S. Army Coastal Engineering Research Council, 1969).

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8 Russell, op. cit., footnote 7.

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16 For a detailed discussion of hurricane climatology see J. Chang, Atmospheric Circulation Systems and Climates (Hawaii: The Oriental Publishing Company, 1972), pp. 95-117.

17 Data sources of swell directions for coastal areas of the Americas include op. cit., footnote 6; Atlas of the Sea and Swell Charts North Pacific Ocean (United States Navy Hydrographic Office, H. O. Pub. No. 799D, 1969) pp. 12; Atlas of Sea and Swell Chart South Pacific (United States Navy Hydrographic Office, H. O. Pub. No. 799B, 1948) p. 12; Russell, op. cit., footnote 7.

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APPENDIX B

Coastal Marine Fauna and Marine Climates of the Americas

Bruce Hayden
Robert Dolan

APPENDIX B

TABLE OF CONTENTS

COASTAL MARINE FAUNA AND MARINE CLIMATES OF THE AMERICAS

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Abstract. The geographic ranges of 968 marine fauna for coastal areas of the Americas excluding the Arctic were analyzed for co-ranges and compared with recent classifications of coastal marine and wave climates. Forty-two co-ranges and thirty-nine characteristic endpoints are reported. Many of the identified faunal boundaries correspond to those of previous studies; and, of the thirty-nine characteristic endpoints, thirty coincided with reported transition regions of the physical environment determined through analysis of the motion fields of the marine and atmospheric fluids. It is proposed that the hydrodynamics of the coastal marine environment give rise to the extant thermal structure of coastal waters and as

such to the distributional patterns exhibited by fauna. The high level of coincidence between biotic and abiotic zones of change along the coast clearly merits using both coastal marine fauna and the hydrodynamics of adjacent waters to establish the marine provinces of the coastal environment.

INTRODUCTION

The distributional patterns of coastal marine fauna have long served as the basis for identification of marine provinces. Implicit in this identification is the assumption that the biogeography of coastal marine fauna reflects the geographic structure of the physical environment. While the temperature is usually assumed to be the primary limiting factor controlling the distribution of coastal marine fauna, attempts to quantify the assumed relationship have been unsuccessful. Valentine (1966) attributed the difficulty to "selecting a way to present the temperature data that is biologically meaningful for a large number of species throughout the entire region."

Valentine further noted that "selection of a single criterion as a 'temperature factor' with which to contrast distributional phenomena is impossible." He recommended the use of combinations of factors but noted that such attempts have been unsuccessful to date.

In 1972, the authors, under the sponsorship of the Office of Naval Research, Geography Programs, began work on the classification of the coastal environments of the Americas. Components of the physical environment were classified independently according to the characteristic motion fields of the atmosphere and oceans near the coastal zone. Simultaneously, analyses were started on the coastal marine and terrestrial fauna and flora of the Americas.

This paper describes the nature of the major latitudinal changes in the distributional structure of selected coastal marine fauna and contrasts these distributions and their endpoints with recent classifications of coastal marine climates (Dolan, Hayden et al., 1972) and coastal wave climates (Hayden and Dolan, 1973) of the Americas excluding the Arctic.

SOURCES OF DATA

Distributional data were collected on coastal marine fauna covering the coastal regions from Point Barrow, Alaska, to Tierra del Fuego at the southern tip of South America, and from Tierra del Fuego to Henry Kater Peninsula on Baffin Island on the east coast of the Americas. Data were recorded on 968 forms, including 167 ascidians, 228 cancroid crabs, 174 majidae crabs, 112 oxystomatous crabs, 121 grapsoid crabs, 64 aplousobranchia, and 102 Mollusca. The major information sources were Van Name (1945), Rathbun (1925, 1930, 1937), and Abbott (1954).

Distributional data on more than 2,000 forms of west-coast Mollusca on which Valentine (1966) based his analyses of molluscan provinces were excluded from this study to permit comparison with Valentine's work. Distributions were included whose endpoints were determined by political boundaries, such as the border between Texas and Mexico. However, note was taken of potential artifacts which might result from this inclusion.

The organization of physical properties of coastal marine waters of the Americas, with which faunal-province boundaries are compared, was taken from the classification of coastal marine waters (Dolan, Hayden et al., 1972) and the classification of coastal wave climates (Hayden and Dolan, 1973).

REVIEW OF THE LITERATURE

While the covariance of climate and terrestrial vegetation has received considerable attention over the years, less effort has been directed to the problem of the covariance of coastal marine biota and the physical environment of coastal marine waters. However, in the available literature a trend is clearly evident for both terrestrial and coastal marine biogeography, characterized by the application of complex variables (air and water masses, streamline functions) rather than single variables (temperature, precipitation, salinity, etc.). With respect to terrestrial vegetation, this trend is of three parts:

1) The early Greeks discerned that thermal conditions associated with seasonally changing solar inclinations formed tropical, temperate, and arctic zones of vegetation.

2) Köppen (1936) integrated thermal and moisture attributes to derive a classification of climates consistent with the distribution of vegetation.

3) More recently, Borchert (1953), Hare (1951), and Bryson (1966) demonstrated that the distribution and movement of air masses as determined through analyses of the characteristic fields of atmospheric motions

define natural climatic complexes whose conditions are spatially homogeneous and which closely approximate the major biomes of North America.

In the case of coastal marine biotic provinces, most of the work to date has centered on establishing covarying relationships between temperature or temperature gradients and the distribution of coastal marine fauna (Hall, 1964; Valentine, 1966). In large part this has been based on physiological studies which demonstrate the importance of thermal-limiting factors affecting both growth and reproduction (Bullock, 1955; Gunter, 1957; Segal, 1961). However, attempts to establish the relationship between temperature gradients and molluscan province boundaries have been unsuccessful (Valentine, 1966). Based on marine biogeography, Hall (1964) defined six marine climates which have characteristic temperature ranges for both the east and west coasts of North America.

Since the distribution of marine biota primarily reflects thermal characteristics, classification of coastal marine climates has been based largely on known distributions of coastal marine fauna (Valentine, 1966; Hall, 1964). However, the difficulty in defining the covariance of thermal characteristics and the distribution of biota has remained chiefly because of dependence on single-temperature measures (Valentine, 1966). After summarizing the works of Bartsch (1912), Newell (1948), and Hall (1960, 1964) and presenting the results of his own analyses, Valentine provided a valuable clue toward solving this problem. In analyzing the basis of molluscan distributions along the west coast, he indicated that several province boundaries coincide with such attributes as:

1) Summer position of tropical waters,
2) changes in hydrographic regimes,
3) upwelling, and
4) eddy systems.

Valentine clearly stressed the role of water-mass types and the characteristic motion fields of coastal marine waters in establishing their thermal structure and the resultant distributional adjustment of coastal marine fauna. Reid (1962) demonstrated that patterns of oceanic circulation in the Pacific are closely related to the distributional structures of zooplankton volumes and phosphate phosphorous content. Damas (1905) noted the importance of cyclonic-circulation gyre in maintaining organisms in a fixed region in the Norwegian sea. Sømme (1933) cited similar conditions for plankton distributions in the Gulf of Maine and in Baffin Bay. Sverdrup, Johnson, and Fleming (1942) stressed the importance of currents as a determining factor in maintaining an endemic population. The existence of free-swimming and planktontic stages in the life cycle of larger coastal marine fauna would be similarly affected by the hydrodynamic motions within coastal waters.

Along the west coast of the United States, hydrographic and faunal patterns are well known and the covarying relationships are clear. Valentine (1966) noted that near Cedros Island in the summer, faunal transitions are related to northward fluxes of tropical waters. Near Point Conception, where faunal changes are pronounced, a change in hydrographic regimes was documented by Reid, Roden, and Wyllie (1958). Dodimead and Hollister (1958) noted circulation changes based on studies of drift bottles at Dixon Entrance along the British Columbia coast. Dixon Entrance is the faunal-province boundary between Aleutian and Oregonian coastal fauna (Valentine, 1966).

The biogeography of coastal marine fauna is best known for north temperate and north subpolar regions. Faunal distributions for the coastal regions from Baja California north to the Arctic Ocean have been studied by Woodward (1856), Fischer (1887), Dall (1899, 1909, 1921), Bartsch (1912), Smith (1919), Schenck and Keen (1936), Newell (1948), Hall (1960, 1964), and Valentine (1966). Along the east coast of the United States and Canada, faunal provinces have been proposed by Milne-Edwards (1838), Dana (1853), Forbes (1856), Woodward (1856), Packard (1863), Stephenson and Stephenson (1954), Coomans (1962), Hall (1964), and Hazel (1970). From these studies five major provinces are generally agreed upon: the Arctic, Nova Scotian, Virginian, Carolinian, and Caribbean, with separating boundaries at 47°, 41°, 35° and 30° North latitude, respectively. Hazel (1970), however, subdivided the Arctic province into Arctic and Labrador provinces with a poorly defined zone of transition along the southern coast of Baffin Island.

Though considerable work has been published on tropical biogeographic provinces, based largely on the distribution of coral, much less literature is available on the tropics or most of South America. Hedgpeth (1957) proposed coastal marine faunal provinces for the world, thereby including the southern hemisphere; however, the boundaries of tropical faunal provinces remain less defined than those of the west and east coasts of North America.

For both coasts of North America, the biogeography of coastal marine fauna has been used to delineate marine climates. The most recent attempts are those of Valentine (1966) for the west coast and Hazel (1970) for the east coast. However, since the information source of these marine climates is biogeographic, it is not confirmed that the boundaries between regions of the various marine climates are functionally related to oceanic and coastal hydrodynamics.

CLASSIFICATION

Dolan, Hayden et al. (1972) developed a classification for coastal marine waters based upon the distribution of water masses and the direction of current flow within the water masses. The classification provided integration of temperature, salinity, and large-scale advection of waters as manifested by the major currents. Subsequently, Hayden and Dolan (1973) formulated a classification scheme for coastal wave climates based on the structure and organization of the atmospheric windfields in coastal regions and over the ocean surface. Since interaction of shoreward-directed waves and the coastal interface give rise to a system of inshore currents and drift direction, the classification implicitly defined coastal regions within which longshore currents are specified on a climatic time scale.

If, in fact, the organization of water masses and motion fields within these water masses generates the thermal structure of the coastal marine environment, then a high level of coincidence between coastal marine faunal province boundaries and the distribution of marine and wave climates should be manifested. The testing of this hypothesis for the coastal regions of the Americas is presented in this paper.

The Coastal-Trend-Grid Coding System (CTG)

In order to reduce the distributional data on the species studied to a machine-processable form, the endpoints of the along-the-coast distribution of each species were numerically coded. While the Marsden and COTED (Valentine 1966) systems of geographic coding were available, their use in analysis of coastal biota is limited because:

1) The grid cells of these systems are smaller than the grid cells for the resolution of species distribution presented in the literature.

2) The grid cells are not numbered consecutively according to the trend of the coastline of the Americas. Consequently, we developed a new grid system. Each grid cell in the new system has a latitudinal thickness of 1°.

For coastal areas with a dominant east-west trend, we added longitudinal divisions to render the length of the included coastline to a size more nearly commensurate with coasts of a north-south orientation. The grid cells were numbered consecutively beginning along the north coast of Alaska moving counterclockwise around the landmass of the Americas. The resulting Coastal-Trend-Grid coding system (CTG) is illustrated in Figures 1 and 2. We excluded the Aleutian Islands, the Gulf of California, and the islands of the Caribbean from the current study to simplify the analysis and the interpretation, particularly in the Caribbean where problems of island biogeography and biotic migration routes are extremely complex. We recorded, according to the CTG system, the distributional endpoints of the 968 forms studied on IBM punch cards.

Co-range Analysis of Coastal Marine Biota

We defined co-range in this study as an along-the-coast distributional extent of two or more organisms. That is, when two or more organisms begin and end their distributions at the same coastal locations, they are said to have co-ranges. If many organisms have identical co-ranges, the co-range thus defined may attain the status of a coastal-marine-biotic province. Given an x, y plot of distributional data, where x is the endpoint of the distribution (by CTG cell numbers) and y is the beginning point of the distribution of these numbers, clusters of distributional data points define co-ranges.

We machine-plotted distributional coordinates for the 968 species of crabs and Mollusca included in this study for the east and west coasts of the Americas. In each plot, clusters of data points were evident, indicating the occurrences of co-ranges and boundaries between co-ranges. In addition, certain values along the x and y axes were more common than others. Such values along the y axis indicate characteristic starting points of distributions. The data in the form plotted clearly indicated that characteristic starting and terminating points of the distributions are not confined to a single CTG location. That is, the zones of transition between co-ranges occur over several adjacent CTG locations. Most of the clusters (co-ranges) and starting and terminating loci were generally within four adjacent CTG locations. Consequently, the data plots were interpreted by four consecutive CTG unit locations and replotted as illustrated in Figures 3 and 4. The resultant co-ranges are indicated by heavy-lined squares and numbered according to the number of species comprising the co-range. The horizontal rows (y axis), as defined by co-range squares, indicate characteristic starting points of distributions (points of lowest CTG cell number); and the vertical columns indicate characteristic endpoints of distributions (points of highest CTG cell numbers).

For the west coast of the Americas, we defined 14 co-ranges, 9 characteristic-distribution, starting-point locations, and 8 characteristic-distribution endpoints (Fig. 3). Along the east coast of the Americas, we defined 28 co-ranges, 10 beginning locations, and 12 endpoint locations (Fig. 4).

While the graphic presentation of the distributional data in Figures 3 and 4 indicates the general level of organization of the fauna studies, the significance of the distributional organization is evident in a comparison or organization of data pairs with that expected by chance alone. The percentage of distributional endpoint data pairs which fall within the co-range CTG squares is 50% for the west coast of the Americas and 56% for the east coast. Assuming a completely random distribution of data pairs, one would expect only 1.9% and 0.7% occurrence within the co-range squares for the west and east coasts, respectively. The departures from randomness are in the range of twenty-five fold, i.e., occurrences within the co-range squares are approximately twenty-five times more frequent than expected by chance alone. In similar manner, beginning loci (low CTG numbers) of distributional pairs as defined by the co-ranges accounted for 78% (west coast) and 72% (east coast) of the total samples as compared to 24% (west coast) and 27% (east coast) expected by chance alone. For termination loci (high CTG numbers) of distributional data pairs, 82% (east coast) and 77% (west coast) of the total samples are accounted for as compared to chance expectations of 21% (east coast) and 24% (west coast).

The most northerly co-range terminus along the west coast, CTG coordinates 2 through 5, is bracketed by two small molluscan discontinuities at Point Barrow and Seward Peninsula (Valentine 1966). Valentine reported molluscan discontinuities at Nunivak Island, Hagemeister Island, and Prince William Sound which we did not record as co-range termini because of the exclusion of the Aleutian Islands. Valentine's next four boundaries, recorded at Dixon Entrance, Puget Sound, Monterey Bay, and Point Conception coincided with the co-range termini 22-25, 29-32, 41-44 and 45-48, respectively. South of Point Conception (at Punta Eugenia and Cabo San Lucas), Valentine reported two additional faunal transitions.

Although a strong discontinuity in Arthropod Decapoda was recorded at Cabo San Lucas, we found no evidence for the faunal transition at Punta Eugenia.

For most of Central and South America, comparisons of co-range termini in previous literature are limited. Hedgpeth (1957) reported faunal-province boundaries at the equivalent CTG locations, 90, 119, 160, and 178. Of these four locations, the first two, both on the west coast of South America, correspond with co-range termini. The two CTG locations along the east coast of South America, 160 and 178, do not align with co-range termini. This disagreement probably stems from the difficulty in assigning accurate endpoints to the distributions in this region. In addition to the two boundaries which correspond to the reports of Hedgpeth, co-range termini at CTG locations 72-75, 82-85, 97-100, 136-140, 151-154, 162-165, 168-171, 182-185, 192-195, 194-197, 205-208, and 215-218 were identified and were not reported by Hedgpeth.

From Yucatan northward we found 6 co-range termini (245-248, 250-253, 266-269, 273-276, 281-284, and 288-291). Termini locations at 268, 273, 285 and 291 have been reported by Hedgpeth (1957) and Hall (1964). Hedgpeth reported a faunal transition in the vicinity of CTG location

261; however, distributions which we identified as terminating at the Texas-Mexico border may be biased in that this area is a political boundary. Hall (1964) reported a faunal transition in the vicinity of Nova Scotia for which we identified no equivalent co-range terminus; however, several forms terminated their distributions in a broad range from CTG 294 to CTG 313 which includes the Nova Scotia region.

Of the thirty-seven co-range termini which we identified, thirty (81%) are located within one CTG cell of the marine-climate boundaries of Dolan, Hayden et al. (1972) and the wave-climate boundaries of Hayden and Dolan (1973). If one considers the co-range boundary at the Texas-Mexico border as an artifact of distributional endpoint reporting and the co-range boundary at Baffin Island as resulting from an edge effect of the CTG system, then the agreement is thirty out of thirty-five co-ranges or 86% correspondence. In either case the degree of covariance is striking. Of the fifteen marine-climate boundaries we identified in 1972, twelve (80%) are matched by co-range termini within one CTG unit. In addition, we then noted a boundary at CTG location 309 (Nova Scotia) which was reported by Hazel (1970) to be a major faunal province boundary.

In Figures 5 and 6 we compared the locations of co-range termini with the transition zones in the marine and wave climates of the coastal regions of the Americas (as we did in 1972 and 1973). Of the seven co-ranges which do not coincide with marine-climate boundaries, two occur at or adjacent to the Amazon and Rio do la Plata river mouths, and both a river mouth (Orinoco River) and a wave-climate boundary occur adjacent to the co-range terminus at CTG locations 213 and 214.

Two co-range termini along the Gulf of Mexico coast (CTG locations 250-253 and 266-269) also have no association with marine-climate boundaries. The co-range boundary at 183-186 along the Brazilian Coast does not match a boundary in the physical environment. The nearest boundary is at CTG location 178 and coincides with a marine-faunal province boundary reported by Hedgpeth (1957). The co-range boundary at 162-165 along the coast of Argentina does not coincide with any of the boundaries reported by us in 1972 or 1973. Of the eleven wave-climate boundaries reported by Hayden and Dolan (1973), twelve (67%) are within one CTG unit of co-range termini. If we had included the faunal boundary near the Aleutian Islands reported by Valentine (1966) and the faunal boundary at CTG location 178 reported by

Hedgpeth (1957), both of which coincide with wave-climate boundaries, in our comparison, the percentage correspondence would be higher (78%).

Co-range termini occur in the vicinity of the Orinoco and Amazon rivers. In each case a wave-climate boundary coincides with the co-range terminus location. The direction of both the offshore and longshore currents is from west to east; i.e., the co-range termini and wave-climate transition zones are down-current from the river mouth, suggesting that the dispersal of some forms may be controlled by the prevailing westward currents. In the case of the co-range terminus at the outfall of the Rio de la Plata in Argentina, the terminus is centered at the river mouth. The longshore and offshore current directions in this area are both variable and as such would not tend to cause a displacement of the co-range terminus from the river outfall. In the case of the Rio de la Plata, salinity may be a dominant limiting variable. The co-range terminus at the outfall of the Rio Grande is believed to be an artifact of reports of endpoints of distributions for North America which excluded Mexico from the reporting area of coverage. However, Hedgpeth (1957) reported a faunal transition in this area; thus the possibility remains that the co-range terminus at this location may be actual.

The co-range terminus at the junction of peninsular Florida with the Florida panhandle is not reflected in any of the marine-climate transitions; however, a case can be made for geologic control in this location. Peninsular portions of the Gulf coast of Florida are dominated by calcareous sands and sediments characteristically associated with mangroves; while along the panhandle area, quartz sands and muds dominate. Three of the marine-climate boundaries reported by us in 1972 and 1973, for which no matching co-range termini have been located (CTG coordinates 18, 178 and 309) were reported by other investigators to be locations of faunal change. Valentine (1966) reported faunal changes immediately to the north and south of the Aleutian Islands' juncture with mainland Alaska, which would coincide with our reported wave-climate boundary in 1973. At CTG coordinates 178 and 309, Hedgpeth (1957) and Hazel (1970) reported faunal transitions which coincide with boundaries in the marine climates. Of the marine-climate boundaries for which we have not recognized or reported a faunal boundary, two are located along the Caribbean coast and one along the southern coast of western Mexico. Each instance occurs in thermally uniform tropical waters and the physical changes encountered are apparently within the tolerance limits of tropical forms.

In general, the poorest fit between the locations of co-range termini and the boundaries of the marine climates are along the southern coast of South America. In large part this results from the relatively small data set of faunal distributions for these areas and from imprecision in the reports of distributional endpoints in these coastal areas.

DISCUSSION

We have made no attempt to assign the status of province to any of the co-ranges or groups of co-ranges which we identified. We made this decision in part because of the confusion in nomenclature proposed by various authors for the provinces; Dall (1921) proposed a nomenclature based on a generalized terminology of marine climates even though identification of the provinces depended upon biogeographic analyses. On the other hand, Coomans (1962) and Valentine (1966) proposed a province nomenclature based on the happenstance of geographic location. Both Hall (1964) and Hazel (1970) proposed a marine-climate nomenclature and a place-name nomenclature for biogeographic provinces. Unlike the case of the North American and Eurasian boreal forests, whose comparison is aided by knowledge of community structure, dominant life forms, and ecologic functions upon which terrestrial-vegetation nomenclature is based, knowledge of similar aspects of coastal marine communities is incomplete. Although we noted a high degree of covariance between biotic and abiotic components of the coastal environments of the Americas, the respective boundaries or transition zones did not coincide to the degree. It was the exception rather than the rule that the center of a CTG unit-length co-range terminus exactly matched the position of a boundary in the marine or wave climate. However, centers in over 80% of the co-range termini were within three CTG units of a physical transition zone. Therefore, if a system of nomenclature were to be structured, two separate systems should be constructed for the marine climates and faunal provinces, respectively.

For the purposes of this paper, it suffices to note that the geographic covariance of the structure of faunal distributions and coastal-marine climates, based on the study of coastal and oceanic hydrodynamics, is striking and merits continued investigation. Concurrently, study of the organizational structure of coastal marine biotic communities and their ecologic function and physiology will lead to increased understanding of the mechanisms responsible for the high degree of covariance between the physical and biological components.

FIGURE LEGENDS

FIG. 1. Coastal-trend-grid coordinate system for North America.

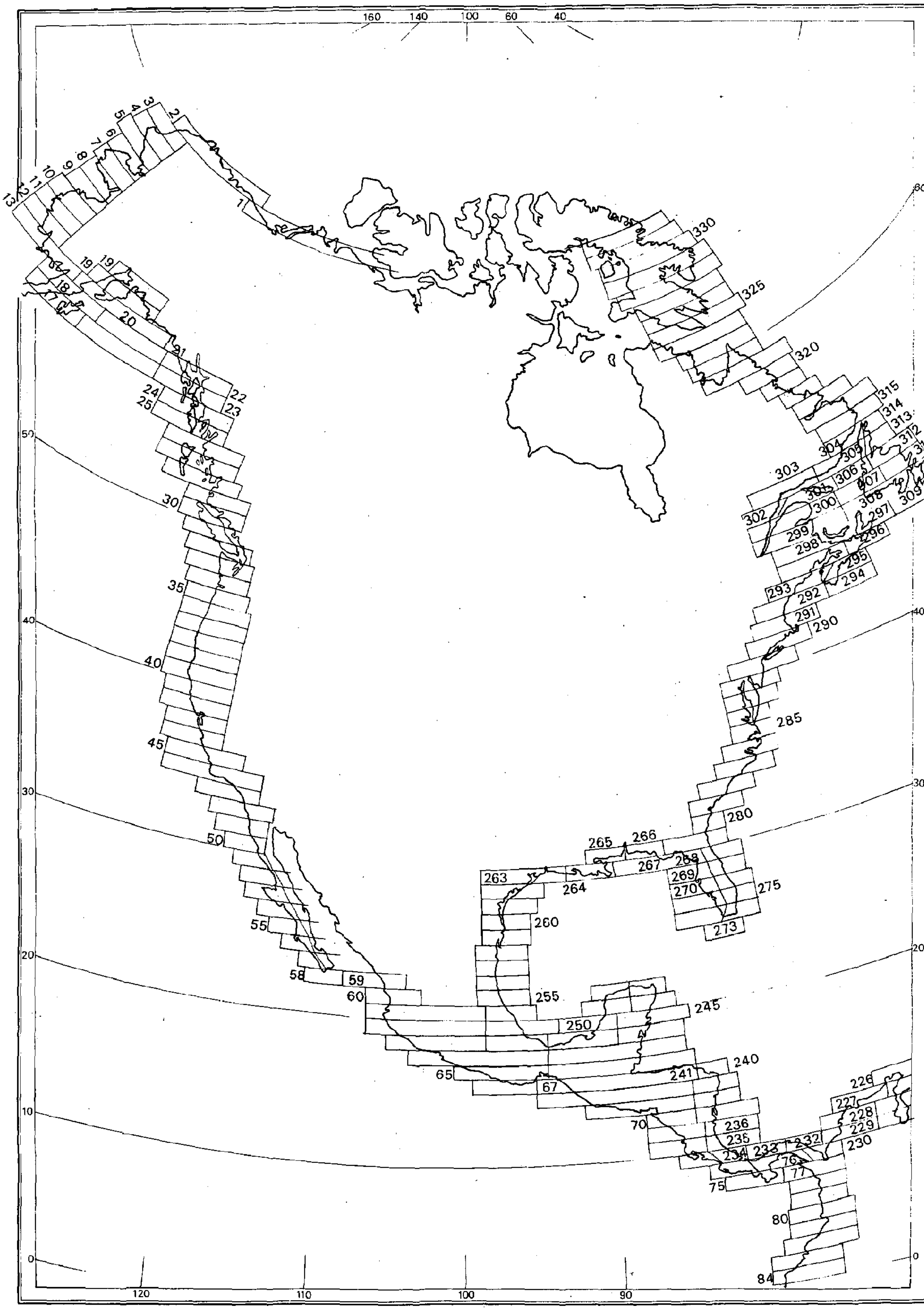
FIG. 2. Coastal-trend-grid coordinate system for South America.

FIG. 3. Co-ranges and co-range termini for the west coast of the Americas by coastal-trend-grid cell numbers. Co-ranges are indicated by heavy-lined squares with the number of forms in the co-range indicated. Rows and columns indicate co-range termini. Individual points indicate range of single forms.

FIG. 4. Co-ranges and co-range termini for the east coast of the Americas by coastal-trend-grid cell numbers. Co-ranges are indicated by heavy-lined squares with the number of forms in the co-range indicated. Rows and columns indicate co-range termini. Individual points indicate range of single forms.

FIG. 5. Co-range termini and marine- and wave-climate boundaries for North America. Shaded coastal-trend-grid cells indicate co-range distributions. Open circles indicate positions of wave-climate boundaries (after Hayden and Dolan, 1973) and solid circles indicate marine-climate boundaries (after Dolan, Hayden, et al., 1972).

FIG. 6. Co-range termini and marine- and wave -climate boundaries for South America. Shaded coastal -trend-grid cells indicate co-range distributions. Open circles indicate positions of wave-climate boundaries (after Hayden and Dolan, 1973) and solid circles indicate marine-climate boundaries (after Dolan, Hayden, et al., 1972).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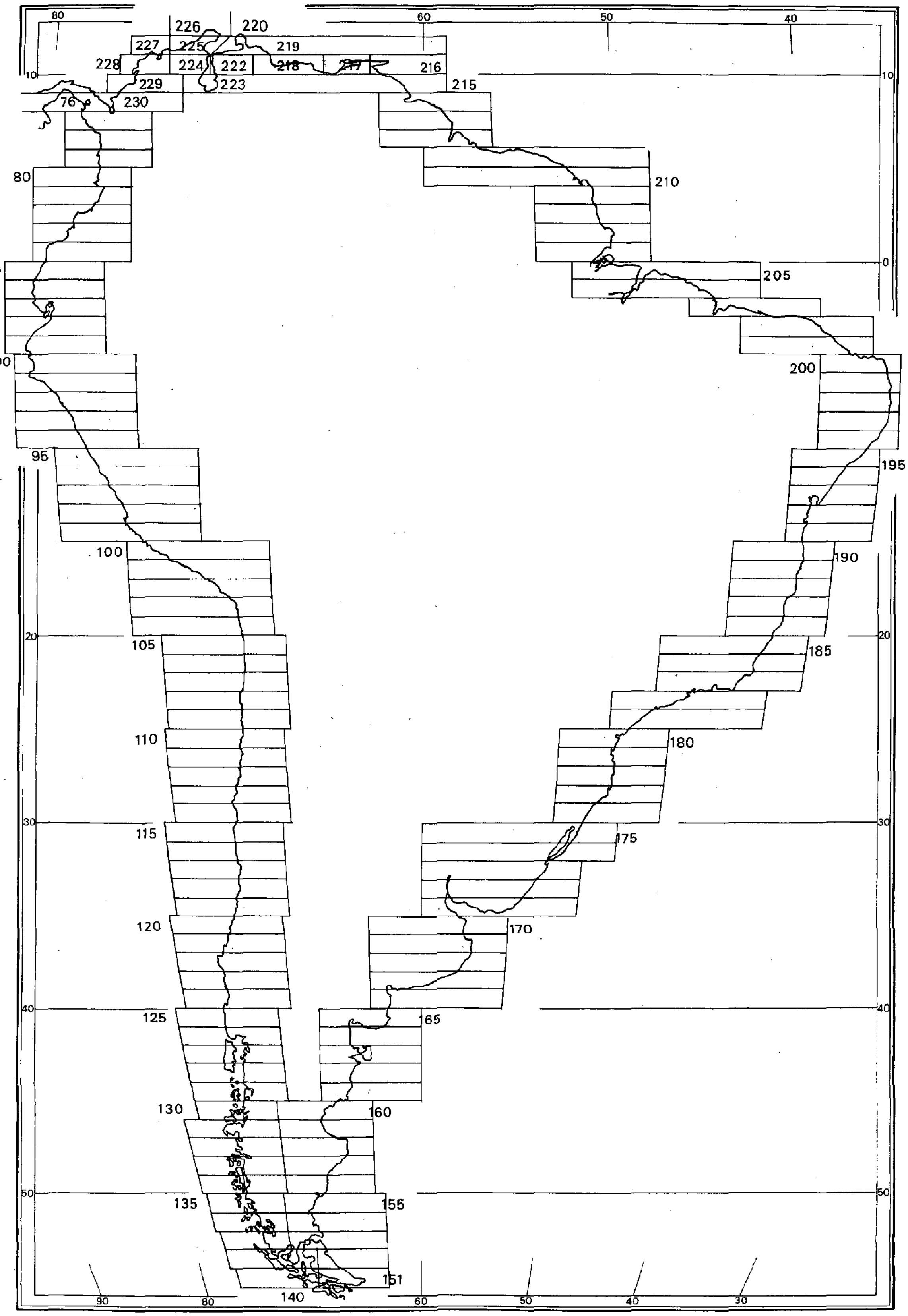
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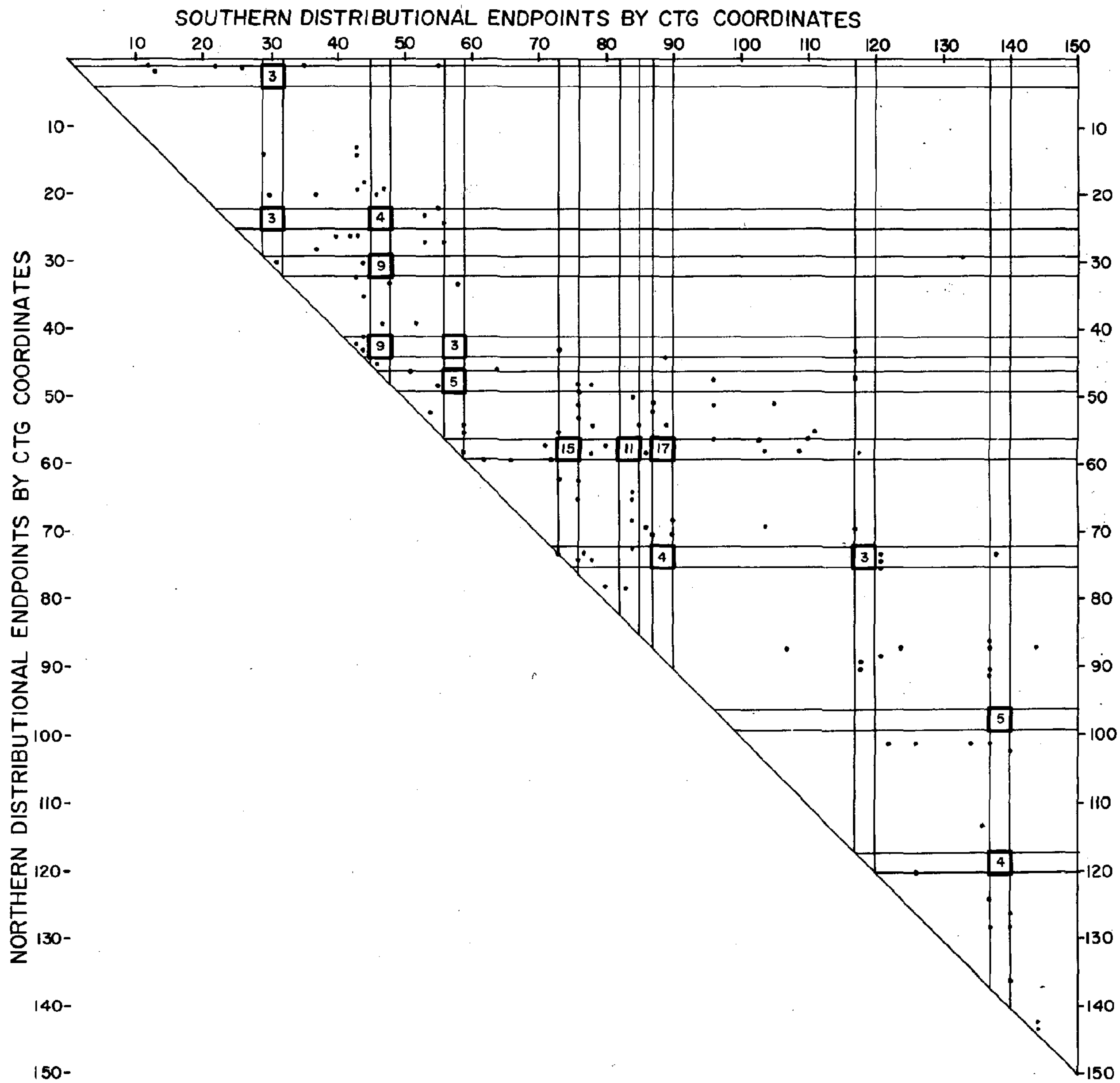
SOUTHERN DISTRIBUTIONAL ENDPOINTS BY CTG COORDINATES
NORTHERN DISTRIBUTIONAL ENDPOINTS BY CTG COORDINATES
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3
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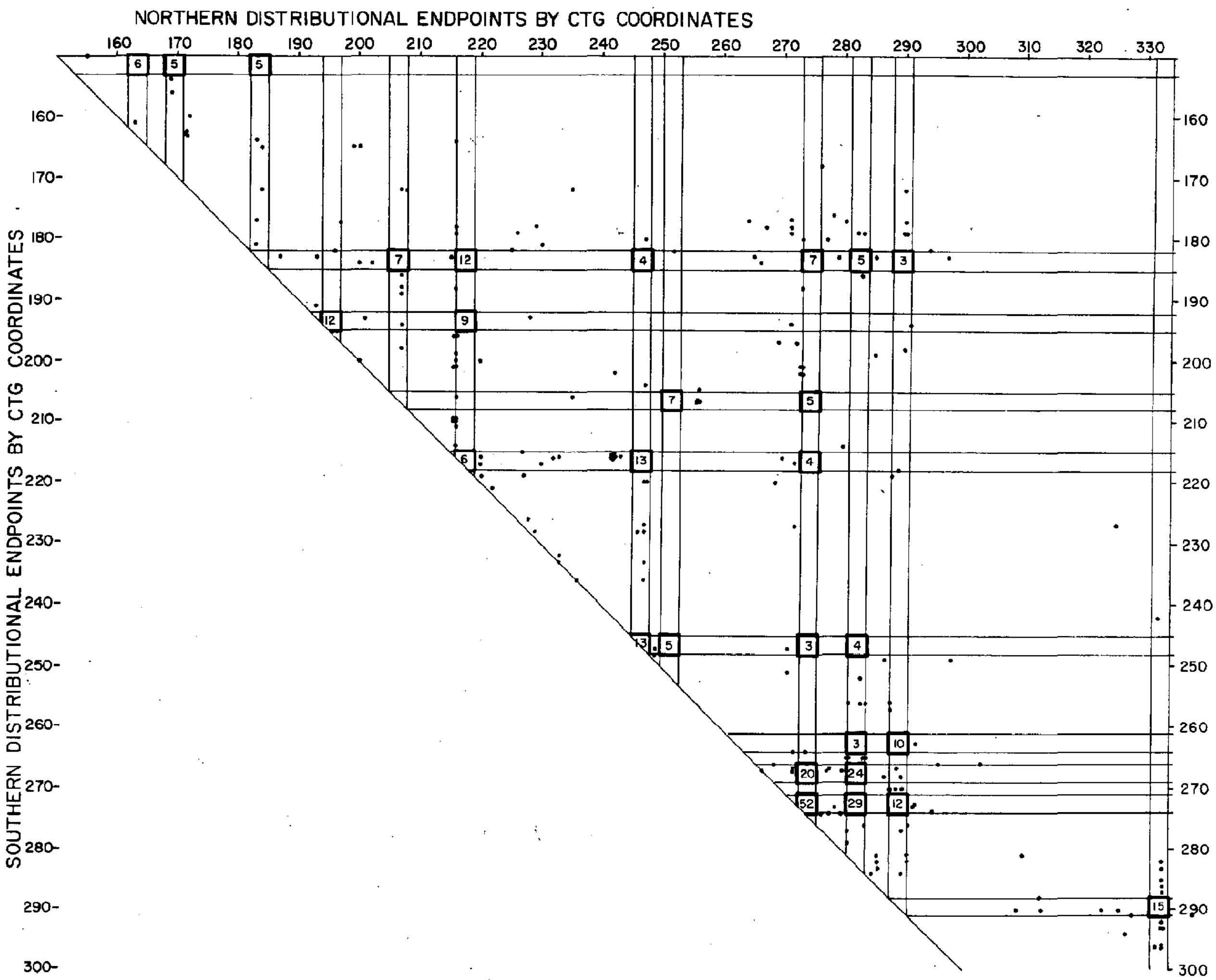
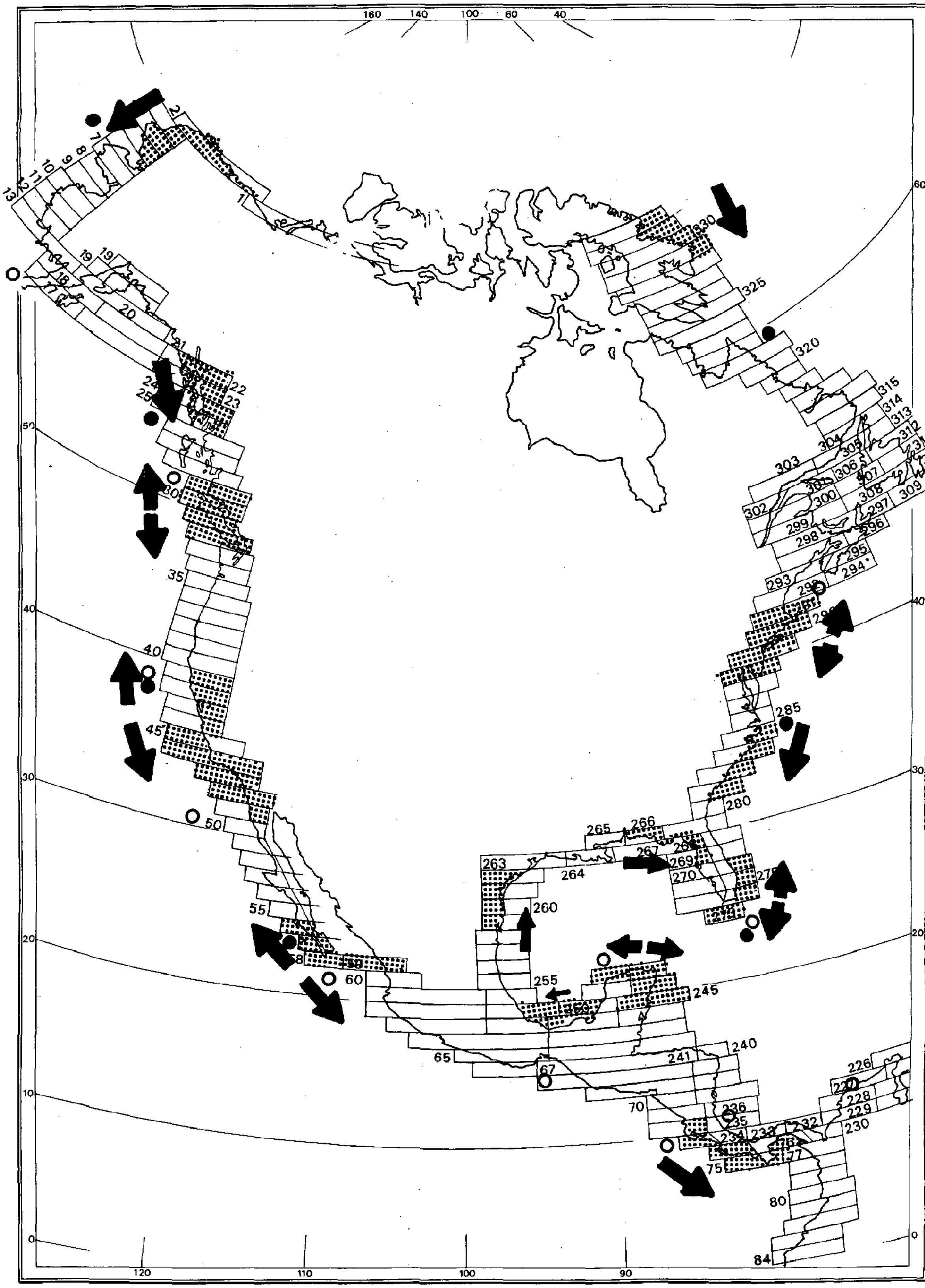
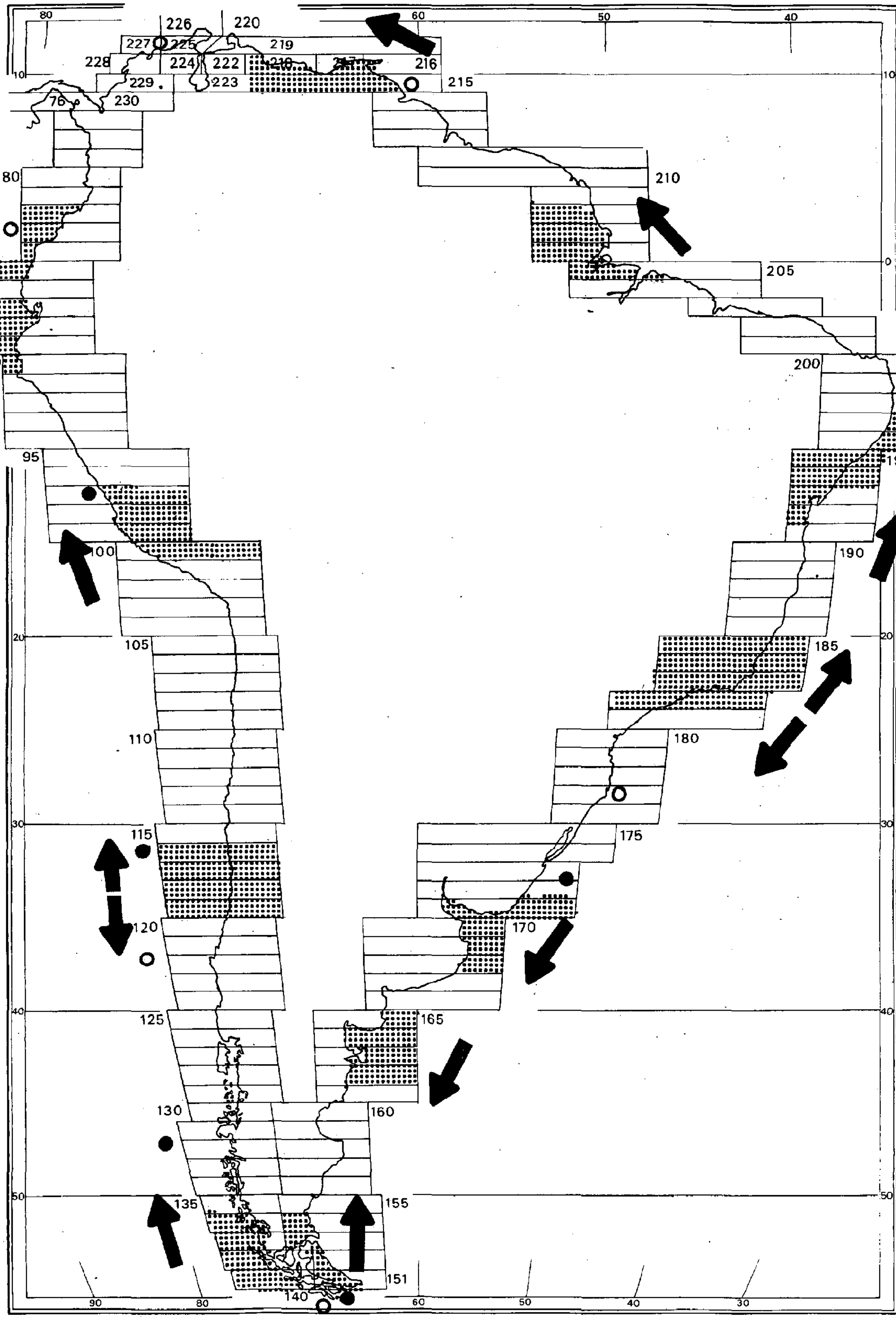
15
11
17
4
3
5
4



NORTHERN DISTRIBUTIONAL ENDPOINTS BY CTG COORDINATES
160 170 180 190 200 210 220 230 240 250 260 270 280 290 300 310 320 330
SOUTHERN DISTRIBUTIONAL ENDPOINTS BY CTG COORDINATES
160 170 180 190 200 210 220 230 240 250 260 270 280 290 300
6 5 5
7 12 4 7 5 3
12 9
7 5
6 13 4
13 5 3 4
3 10
20 24
52 29 12
15





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222
218
217
216
229
223
215
76
230
10
10
210
80
85
205
0
0
90
200
195
95
100
190
185
20
20
105
180
110
175
30
30
115
170
120
165
125
40
40
160
130
155
135
50
50
151
140
90
80
60
50
40
30

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APPENDIX C

An Assessment of Remote Sensing as a Tool in Classifying Coastal Landscape Elements

Mary Vincent
Jeffrey Heywood
Linwood Vincent
Robert Dolan
Bruce Hayden

APPENDIX C

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PREFACE

Remote sensing, or the use of imagery for the identification and study of landscape features and phenomena, has potential as an efficient means of acquiring information and data for land-use management and environmental investigations. These uses recognize the existence of natural environmental complexes that recur spatially and exhibit characteristic geographic distributions.

There are volumes of literature on remote sensing dealing with capabilities, potential, special uses, evaluations for particular types of studies, suitable scales, and special techniques. However, most papers are limited in scope to either a single type of imagery or a single application and are directed to the trained interpreter with special equipment.

This paper presents observations on the use of several types of imagery in the investigation of coastal environmental complexes. It is not intended as an imagery recognition key for coastal features but as a guide to efficient imagery selection and application in the coastal environment.

ABSTRACT

In order to assess the applicability of remote-sensing imagery and data to the coastal environment classification process, a study of the utility of various types of imagery for the identification of coastal features was undertaken for sites along the United States coastline. The study has shown that recognition ratings can be used to summarize appropriate applications of imagery types. Results indicate that color infrared photography provides the best base for most studies.

INTRODUCTION

At the University of Virginia our research team developed a method of classifying coastal environments described in Classification of Coastal Environments, Procedures and Guidelines (Dolan and Hayden 1973). The classification focused on the interaction in two parts; along-the-coast ($\hat{\ell}$-system) and across-the-coast ($\hat{\eta}$-system).

An earlier along-the-coast investigation by the same team dealt with three major environmental components: atmospheric processes, marine processes, and terrestrial materials. Twelve coastal interface types were identified and related to a dominant process (Dolan et al. 1972).

An across-the-coast classification dealt with the area between the edge of the continental shelf and the inland limit of marine-process influence. This classification provided a tentative stratification of zones within one interface type and discussed the potential of the $\hat{\eta}$-system (Resio et al. 1973).[1]

---

[1]More detailed analyses of components of the environment as organized across the coast are presented in Systematic Variations in Offshore Bathymetry (Resio et al. 1974), Systematic Variations in Inshore Bathymetry (Hayden et al. 1974) and Systematic Variations in Barrier-Island Topography (Vincent et al. 1974).

During our investigations of coastal environments, we found that topographic maps did not consistently provide adequate resolution for the identification of coastal materials, configurations, and naturally occurring zones. Therefore, we studied several types of imagery to evaluate the possibility of using remote-sensing imagery as a data base in the classification system.

IMAGERY

Only imagery of coastlines of the United States was used in this study. We examined the following types of imagery for features interpretable as processes, coastal zones, and regional patterns:

Aerial Photography

1. Black-and-White Panchromatic
2. Black-and-White Infrared
3. Color
4. Color Infrared
5. Skylab

Satellite Imagery

1. ERTS, MSS bands 4,5,6,7 (B&W)
2. ERTS, color composite
3. Satellite Scanning Radiometer (B&W)

We then listed coastal features and correlated them on a matrix (Table 1) to the twelve interface types which were identified in the along-the-coast

TABLE 1

Definition of Interface Types by Characteristic Composition of Landscape Elements

Landscape Elements	Sand Beach	Barrier-Chain Coast	Pocket-Beach Coast	Sand Beach with Rock Headlands	Shingle or Cobble Beach	Rocky Coast	Delta Shoreline	Estuary	Fjord Coast	Coral-Reef Shoreline	Mangrove Shoreline	Open Coast, Marsh, or Mudflat
Relief												
High Relief	o	✓	✓	✓	✓	✓	o	✓	✓	o	o	o
Low Relief	✓	✓	✓✓	✓✓	✓✓	✓✓	✓	✓✓	x	✓	✓	✓
Coastal Plain	✓✓	✓✓	x	x	x	x	✓✓	✓	x	✓✓	✓✓	✓✓
Shore Material												
Rocky, mainland	x	x	✓	✓	o	✓	x	x	✓	x	x	x
Rocky, skerry	x	x	•	o	•	✓	x	o	•	x	x	x
Shingle	x	x	•	x	✓	•	x	o	x	x	x	x
Sand, sandy	✓	✓	✓	✓	x	o	•	o	x	•	•	x
Siltage	x	x	x	x	o	•	✓	✓	x	x	•	•
Coral, fringing reef	•	•	o	o	x	x	x	x	x	✓	•	x
Coral, barrier reef	•	•	o	o	x	x	x	x	x	✓	•	x
Topographic Forms												
Coastline	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Promontory	o	x	✓	✓	o	✓	x	o	✓	x	x	x
Cliff	x	x	•	o	•	•	x	o	✓	x	x	x
Truncated Spur	x	x	x	x	x	x	x	x	✓	x	x	x
Barrier	o	✓	x	x	o	x	x	x	x	•	•	o
Alluvial Plain	x	x	x	x	x	x	✓	x	x	x	o	o
Natural Levee	x	x	x	x	x	x	✓	x	x	x	x	x
Dune, stable (vegetated)	•	✓	x	x	x	x	x	x	x	x	x	x
Dune, nonstable (nonvegetated)	•	✓	x	x	o	x	x	x	x	o	o	x
Tidal flat	o	•	o	x	o	o	o	✓	x	o	o	✓
Swash zone	✓	✓	✓	✓	✓	✓	o	o	o	x	o	o
Beach	✓	✓	x	✓	✓	x	x	x	x	o	x	o
Beach crest	✓	✓	x	•	✓	x	x	x	x	x	x	x
Hydrographic Forms												
Bathyorographic variance												
great	o	x	o	x	x	✓✓	x	o	x	o	o	o
little	✓	✓	✓✓	✓✓	✓✓	✓	✓	✓	✓*	✓✓	✓✓	✓✓
flat	✓✓	✓✓	x	o	o	o	✓✓	o	✓**	✓	✓	✓
Submarine bar	•	✓	x	x	o	x	o	o	x	o	o	o
Shoals	o	•	x	x	o	x	o	o	x	o	o	o
Channel												
hanging valley	x	x	x	x	x	x	x	x	✓	x	x	x
mouth (river)	o	o	o	o	o	o	✓	✓	✓	o	o	o
inlet	o	✓	x	x	o	x	x	x	x	•	•	o
tidal channel	o	✓	x	x	o	x	x	x	x	•	•	o
distributary	x	x	x	x	x	x	✓	x	x	x	x	x
drainage pattern												
Bay												
open bay or bight	✓	x	x	✓	✓	o	x	x	x	o	o	o
bayhead beach	o	x	✓	x	✓	o	x	x	x	x	x	x
funnel sea	x	x	x	x	x	x	o	✓	x	x	o	o
trough, u-shape valley	x	x	x	x	x	x	x	x	✓	x	x	x
closed bay or lagoon	o	✓	x	x	o	x	x	x	x	•	•	o
Site-Specific Features												
Berm	✓	✓	o	o	•	x	o	x	x	x	x	x
Beach ridge	o	o	x	o	o	x	o	x	x	x	o	o
Overwash mark	•	•	x	o	x	x	o	x	x	x	x	x
Spit	•	•	o	o	•	o	o	o	x	x	o	o
Cusp	•	•	•	•	•	x	x	x	x	x	x	x
Tidal delta	•	•	x	o	o	x	•	o	x	x	x	x

Process Features
- Wave approach
- Wave breaking, breakers
- Water mass
- River plume
- Sediment, in suspension

Occur universally, with the exception that coral does not occur in waters with large amounts of suspended sediment.

✓ = occurs (✓✓ most often occurs) as a defining characteristic
• = associated with; typically occurs but not always
o = can and does occur but not typically associated with
x = occurs rarely, if ever

* Outside of channel
** Within channel

classification.[2] This matrix provides the simple organization of coastal features into patterns which define interface types by the presence, absence, or association of attributes. This matrix aids in understanding coastal form complexes and serves as a key to combinations and associations in imagery interpretation.

The matrix of coastal features and the certainty with which these features can be recognized on each type of imagery is listed in Table 2. For a comparison of imagery with topographic maps, Table 3 provides our estimates of the relative certainty with which the coastal features can be interpreted on various scales of maps and indicates the level of accuracy with which measurements can be made.

DISCUSSION

The matrices and tables (Tables 2-6) present the results of an evaluation of eight types of imagery for use in obtaining information on selected elements of the coastal landscape. The foremost problem in conducting and presenting this study is the subjectivity inherent to remote-sensing interpretation. Levels of

---

[2] A glossary of coastal features and interface types is given in Appendix B.

Landscape Elements	Black and White			Black-and-White Infrared			Color			Color Infrared			ERTS					
	1:10,000 ±5,000	1:40,000 ±20,000	1:120,000 ±40,000	1:10,000 ±5,000	1:40,000 ±20,000	1:120,000 ±40,000	1:10,000 ±5,000	1:40,000 ±20,000	1:120,000 ±40,000	1:10,000 ±5,000	1:40,000 ±20,000	1:120,000 ±40,000	4	5	6	7	Color Comp	Scanning Radiometer
Relief													1	2	1	2	1	0
High Relief	2	1	1	2	1	1	2	1	1	2	2	2	1	2	1	2	1	0
Low Relief	2	1	1	2	1	1	2	1	1	2	2	2	1	2	1	2	1	0
Coastal Plain	2	1	1	2	1	1	2	1	1	2	2	2						
Shore Material																		
Rocky, mainland	3	3	1	3	2	1	3	2	1	3	2	1	0	0	0	0	0	0
Rocky, skerry	3	3	1	3	3	1	3	3	2	3	3	1	1	1	1	1	1	0
Shingle	3	1	1	3	1	1	3	1	1	3	1	1	0	0	0	0	0	0
Sand, sandy	3	3	1	3	3	1	3	3	2	3	3	1	0	1	0	0	2	0
Siltage	3	3	1	3	3	1	3	3	1	3	3	1	0	1	1	1	0	0
Coral, fringing reef	3	2	1	3	2	1	3	2	1	3	2	1	1	1	0	0	0	0
Coral, barrier reef	3	2	1	3	2	1	3	2	1	3	2	2	1	1	0	0	0	0
Topographic Forms																		
Coastline	3	3	3	3	3	3	3	3	3	3	3	3	2	2	3	3	3	2
Promontory	3	3	3	3	3	3	3	3	3	3	3	3	2	3	3	3	3	0
Cliff	2	1	0	2	1	0	2	1	0	2	1	0	0	0	0	0	0	0
Truncated Spur	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	0
Barrier	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	1
Alluvial Plain	3	3	2	3	2	2	3	3	2	3	3	3	1	1	2	2	3	0
Natural Levee	3	3	1	3	2	1	3	3	1	3	2	2	1	1	1	2	1	0
Dune, stable (vegetated)	3	3	0	3	3	0	3	3	2	3	3	2	1	1	0	0	0	0
Dune, nonstable (nonvegetated)	3	3	0	3	3	0	3	3	2	3	3	2	1	1	0	0	0	0
Tidal flat	3	3	1	3	3	2	3	3	3	3	1	3	1	1	1	1	1	0
Swash zone	3	3	0	3	3	0	3	2	0	3	2	0	0	0	0	0	0	0
Beach	3	3	0	3	2	0	3	3	1	3	2	1	0	0	0	0	0	0
Beach crest	3	3	0	3	3	0	3	3	1	3	2	1	0	0	0	0	0	0
Hydrographic Forms																		
Bathyorographic variance																		
great	3	3	2	0	0	0	2	1	1	2	1	1	1	0	0	0	0	0
little	3	3	2	0	0	0	2	1	1	2	1	1	1	0	0	0	0	0
flat	3	3	2	0	0	0	2	1	1	2	1	1	1	0	0	0	0	0
Submarine bar	3	3	1	3	3	2	3	3	1	3	3	2	1	1	0	0	0	0
Shoals	3	3	1	3	3	2	3	3	2	3	3	3	1	1	0	0	0	0
Channel																		
hanging valley	3	1	0	2	1	0	3	1	0	2	1	0	0	0	0	0	0	0
mouth (river)	3	3	2	3	3	3	3	3	2	3	3	3	2	2	3	3	3	3
inlet	3	3	2	3	3	2	3	3	3	3	3	3	3	3	3	3	3	0
tidal channel	3	3	2	3	3	2	3	3	2	3	3	3	1	1	2	2	1	0
distributary	3	3	2	3	3	2	3	3	2	3	3	3	1	1	2	2	1	0
drainage pattern	3	2	1	3	3	2	3	2	2	3	3	2	1	2	2	3	1	0
Bay																		
open bay or bight	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	1
bayhead beach	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	0
funnel sea	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	1
trough, u-shape valley	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	1
closed bay or lagoon	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	0
Site-Specific Features																		
Berm	2	2	0	3	2	0	3	1	0	3	1	0	0	0	0	0	0	0
Beach ridge	3	3	1	3	3	2	3	3	1	3	3	3	2	2	1	1	0	0
Overwash mark	3	3	0	3	3	1	3	3	0	3	1	1	0	0	0	0	0	0
Spit	3	3	3	3	3	3	3	3	3	3	3	3	2	2	2	2	2	0
Cusp	3	3	0	3	3	0	3	3	0	3	2	1	0	1	1	2	0	0
Tidal delta	3	3	0	3	3	0	3	3	0	3	1	1	0	0	0	0	0	0
Process Features																		
Wave approach	3	3	1	0	0	0	3	2	1	3	3	3	0	0	0	0	0	0
Wave breaking, breakers	3	3	1	3	3	2	3	3	1	3	3	3	0	0	0	0	0	0
Water mass	0	1	1	0	0	0	0	1	1	1	1	1	2	1	0	0	0	2
River plume	3	3	3	0	0	0	3	3	3	3	3	3	3	2	0	0	1	1
Sediment, in suspension	3	3	3	0	0	0	3	3	3	3	3	3	3	2	0	0	1	1
Vegetative Life-Forms																		
Upland Vegetation (moist soils)	2	2	0	3	3	1	3	2	2	3	3	3	3	2	2	2	2	0
wooded	2	2	0	3	3	1	3	2	1	3	3	3	0	0	0	0	0	0
shrubby	2	2	0	3	3	1	3	2	1	3	3	2	0	0	0	0	0	0
grass	2	2	0	3	3	1	3	2	1	3	3	2	0	0	0	0	0	0
Wetland Vegetation (wet soils)	2	2	0	3	3	1	3	2	2	3	3	3	3	2	2	2	2	0
wooded swamp	2	2	0	3	3	1	3	2	1	3	3	2	1	1	1	1	1	0
shrub swamp	2	2	0	3	3	1	3	2	1	3	3	2	1	1	1	1	1	0
grass - tidal marsh	2	2	0	3	3	1	3	2	1	3	3	3	1	1	1	1	1	0
salt marsh	2	2	0	2	2	1	3	2	1	3	3	2	1	1	1	1	1	0
freshwater marsh	2	2	0	2	2	1	3	2	1	3	3	2	1	1	1	1	1	0
submerged aquatic plants	2	2	0	0	0	0	2	0	0	3	2	1	1	1	1	1	1	0
Desert vegetation (dry soils)	3	3	0	3	3	1	3	3	2	3	3	3	2	2	2	2	2	0
Vegetated/non-vegetated areas distinguishable	3	3	1	3	3	1	3	3	3	3	3	3	0	0	0	0	0	0
Upland/wetland vegetation areas distinguishable	2	2	0	3	3	1	3	2	2	3	3	3	2	2	2	2	2	0

3 = element quickly and easily recognized
2 = element fairly easily recognized
1 = interpretation doubtful or recognition poor
0 = element cannot be recognized

TABLE 2

Recognition of Landscape Elements on Imagery of Various Types and Scales

TABLE 3

Recognition of Landscape Elements on Topographic Maps
of Various Scales, with Degree Accuracy
of Quantitative Extraction Indicated

Landscape Elements	1:24,000	1:50,000	1:62,500	1:100,000	1:250,000	1:500,000	1:1,000,000	1:5,000,000
Relief								
High Relief	4A	4A	4A	4B	4C	3C	3C	2C
Low Relief	4A	4A	4A	4B	4C	3C	3C	2C
Coastal Plain	4A	4A	4A	4B	4C	3C	3C	2C
Shore Material								
Rocky, mainland	3	3	3	2	2	2	2-1	1
Rocky, skerry	3	3	3	2	2	2	2-1	1
Shingle	3	3	3	2	2	2	2-1	1
Sand, sandy	3	3	3	2	2	2	2-1	1
Siltage	3	3	3	2	2	2	2-1	1
Coral, fringing reef	4	4	4	4	4	3	2-1	2-1
Coral, barrier reef	4	4	4	4	4	3	2-1	2-1
Topographic Forms								
Coastline	4A	4A	4A	4A	4A	4A	4A	4B
Promontory	4A	4A	4A	4A	4B	3C	2C	2C
Cliff	4B	3B	3C	2C	2C	2C	2C	1
Truncated Spur	4A	4A	4B	3B	3C	3C	1	1
Barrier	4A	4B	4B	4B	4C	4C	4C	3C
Alluvial Plain	4A	4A	4A	4B	4C	3C	3C	2C
Natural Levee	4B	4B	4B	4B	4C	1	1	1
Dune, stable (vegetated)	2C	2C	2C	1	1	1	1	1
Dune, nonstable (nonvegetated)	2C	2C	2C	1	1	1	1	1
Tidal flat	4A	4B	3B	2C	2C	2C-1	2C-1	1
Swash zone	1	1	1	1	1	1	1	1
Beach	1	1	1	1	1	1	1	1
Beach crest	3B	1	1	1	1	1	1	1
Hydrographic Forms								
Bathyorographic variance								
great	4A	4A	4A	4A	4A	3A	3A	2B
little	4A	4A	4A	4A	4A	3A	3A	2B
flat	4A	4A	4A	4A	4A	3A	3A	2B
Submarine bar								
Shoals								
Channel								
hanging valley	4A	4B	4B	3C	2C	1	1	1
mouth (river)	4A	4B	4B	4B	4C	3C	3C	3C
inlet	4A	4B	4B	4B	3C	3C	2C	2C
tidal channel	4A	4B	4B	4C	4C	2C	1	1
distributary	4A	4B	4B	4C	4C	3C	2C	2C
drainage pattern	4A	4A	4A	4A	3B	3C	2C	2C
Bay								
open bay or bight	4A	4A	4A	4A	3B	3C	2C	1
bayhead beach	4A	4A	4B	4B	3C	2C	1	1
funnel sea	4A	4A	4A	4A	4B	3C	2C	2C
trough, u-shape valley	4A	4A	4A	4A	4B	4C	3C	2C
closed bay or lagoon	4A	4A	4A	4B	4C	3C	3C	2C
Site-Specific Features								
Berm	2C	2C	2C	1	1	1	1	1
Beach ridge	4A	4B	4B	3C	1	1	1	1
Overwash mark	2C	1	1	1	1	1	1	1
Spit	4A	4B	4B	3	2C	2C	2C	2C
Cusp	1	1	1	1	1	1	1	1
Tidal delta	2C	1	1	1	1	1	1	1
Process Features								
Wave approach	1	1	1	1	1	1	1	1
Wave breaking, breakers	1	1	1	1	1	1	1	1
Water mass	1	1	1	1	1	1	1	1
River plume	1	1	1	1	1	1	1	1
Sediment, in suspension	1	1	1	1	1	1	1	1

Recognition:
- 4 = element clearly presented
- 3 = element fairly clearly presented
- 2 = interpretation doubtful
- 1 - element not presented

Accuracy of Quantitative Extraction
- A = accurate measurements can be made
- B = accuracy marginal; measurements can be taken depending on degrees of accuracy required
- C = cannot or should not take measurements

TABLE 4

Recognition Rating* of Landscape-Element Groups on Various Types and Scales of Imagery (in percent)

Land-Element Groups	Black and White			Black-and-White Infrared			Color			Color Infrared			ERTS					
	1:10,000 ±5,000	1:40,000 ±20,000	1:120,000 ±40,000	1:10,000 ±5,000	1:40,000 ±20,000	1:120,000 ±40,000	1:10,000 ±5,000	1:40,000 ±20,000	1:120,000 ±40,000	1:10,000 ±5,000	1:40,000 ±20,000	1:120,000 ±40,000	4	5	6	7	Color Comp 4,5,7	Scanning Radiometer
Relief	66	33	33	66	33	33	66	33	33	66	66	66	33	66	33	66	33	0
Shore material	100	81	33	100	76	33	100	76	43	100	76	38	14	24	10	10	14	0
Topographic form	97	95	41	97	87	43	97	92	61	97	79	67	38	41	41	43	43	8
Hydrographic form (all)	100	94	67	79	77	63	94	81	67	92	83	77	58	54	56	58	50	6
Channel forms	100	83	50	94	89	61	100	83	61	94	89	78	44	50	66	72	50	0
Bay forms	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	20
Site-specific features	94	94	22	100	94	33	100	89	22	100	61	50	22	28	22	28	11	0
Process features	80	87	60	20	20	2	80	80	60	87	87	87	53	33	0	0	2	27
Vegetative life forms (all)	69	69	0	86	86	31	97	64	39	100	97	78	39	36	36	36	36	0
Upland	66	66	0	100	100	33	100	66	42	100	100	83	33	17	17	17	17	0
Wetland	66	66	0	76	76	29	95	57	33	100	95	71	43	39	39	39	39	0
Desert	100	100	0	100	100	33	100	100	66	100	100	100	66	66	66	66	66	0
Average percent recognition	95	81	34	85	78	41	94	77	52	95	86	76	45	46	41	46	38	5

$$\text{*Rating} = \frac{\text{sum actual recognition each element within group (from Table 2)}}{\text{sum possible recognition each element within group (i.e., 4 times number of elements in group)}} \times 100$$

Table can be interpreted as giving the percent capability of a type and scale of imagery for study of a particular group of landscape elements.

TABLE 5

Landscape Elements Grouped by Scales of Dimensionality

Scale		Landscape Elements	
Region (most of variation on order of 100-500 miles) scale of gross coastal form	GROSS SCALE	1 coastline barrier	2 relief alluvial plain bathyorographic variance mouth (river) channel form trough, bay form lagoon, bay form
Area (most of variation on order of 10-100 miles) scale of differentiation within gross form	MEDIUM SCALE	3 coral reef promontory natural levee tidal channel, channel form distributary, channel form funnel sea, bay form	4 truncated spur inlet, channel form drainage pattern, channel form open bay, bay form bayhead beach, bay form
Site (most of variation on order of 0-10 miles) scale of local character	SMALL SCALE	5 hanging valley, channel form beach ridge spit	6 shore material: rocky shingle sand siltage cliff tidal flat dune beach crest berm tidal delta

Table 5 constructed from Table 3 according to these criteria

1 elements clearly presented on 1:1,000,000 topographic maps
2 elements fairly clearly presented on 1:1,000,000 topographic maps
3 elements clearly presented on 1:250,000 topographic maps
4 elements fairly clearly presented on 1:250,000 topographic maps
5 elements clearly presented on 1:62,500 topographic maps
6 elements fairly clearly presented on 1:62,500

The following features do not appear on topographic maps: process features, overwash mark, cusp, beach.

The vegetative life-forms 1) are not describable by these scales and 2) do not appear with consistency on topographic maps and so are not included.

TABLE 6

Recognition Rating of Landscape-Element Groupings of Scales of Dimensionality on Various Types and Scales of Imagery (in Percent)

Imagery	Recognition on Regional Scale	Recognition on Area Scale	Recognition on Site Scale	Overall Recognition Capability of Imagery Type
Black and White				78
app. 1:10,000	92	100	96	96
app. 1:40,000	83	92	80	85
app. 1:120,000	69	67	22	53
Black-and-White IR				69
app. 1:10,000	67	100	96	79
app. 1:40,000	56	92	82	77
app. 1:120,000	56	72	27	52
Color				78
app. 1:10,000	83	100	98	94
app. 1:40,000	67	92	80	80
app. 1:120,000	61	78	42	60
Color IR				79
app. 1:10,000	83	100	96	93
app. 1:60,000	75	86	69	77
app. 1:120,000	75	86	44	68
ERTS Imagery				47
MSS 4	56	64	18	46
MSS 5	56	69	22	49
MSS 6	56	67	13	45
MSS 7	64	72	13	50
Color Composite (MSS4,5,7)	58	61	13	44
Skylab Imagery	?	?	?	?
Satellite Scanning Radiometer	11	6	0	7

Overall Recognition of Scales of Dimensionality interpreter training, experience, and understanding of coastal environments can vary considerably. Although an objective presentation of subjectively obtained results is impossible, the numerical ratings (Tables 4 and 6) do provide an effective relative evaluation of the imagery types which is meaningful to most readers.

A second problem in studying the applicability of each type of imagery is the variability of image quality. Although the quality of visual definition is effected by atmospheric conditions, film exposure, and quality of sensor and film, calibration of these factors is difficult. The results presented here can be regarded as representing what should be expected with good to excellent imagery.

Imagery availability is a third problem. Since no single agency acts as a clearinghouse for aerial photography, it may take several weeks to locate the desired imagery at the desired scale. The delivery time on most orders is, at best, a month because prints or transparencies are made on request. Resolution varies with imagery type but improves as the scale increases; in cases where the desired scale is not available, commensurate resolution might be obtained on other types of imagery at the same or different scale.

The particular landscape elements chosen for this study reflect a subjective bias. From all the possible elements which could have been studied, we selected only those considered significant in defining the classification of interface types or in delineating across-the-coast zones; such elements as mudlumps and kelp were not included. Other elements represent prior arbitrary categorization; i.e., the categories of relief. The nomenclature was intended to be descriptive in order to avoid genetic prejudgment of coastal types: "Rocky" is descriptive yet encompasses glacial, faulted, and volcanic coasts. Terms having a process or generic context could not be completely avoided; i.e., natural levee, truncated spur, trough bay.

This evaluation is based on the observations of two untrained interpreters with a modest sample of imagery. Although there is a large body of remote-sensing literature, it was of little assistance in our study. In many papers differentiation between conjecture and actual observation was difficult. In addition, the major concern of many articles was on a sensor technology rather than image application. At present, the remote-sensing field is extremely transitory; continuing studies will undoubtedly refine the applicability of the various types of imagery and scales.

SUMMARY AND CONCLUSIONS

Our study focused on the evaluation of eight types of imagery for use as an information source in coastal investigations. Our conclusions and observations may be summarized as follows:

1. Much of the existing literature is of little value in investigations concerned with the applications of various types of imagery.
2. The consistency in quality and scale coverage of imagery types is poor.
3. The difficulties in ascertaining the holding agency of necessary imagery and the acquisition procedures are hindrances to studies requiring imagery.
4. In order to diminish the effects of individual subjectivity, several interpreters should be involved in producing an evaluation; at least two interpreters should be employed in any study using imagery as a data base.
5. Because some coastal landscape elements do not appear or are poorly developed (like fjords) along coasts of the continental United States, a study of imagery for foreign areas would be extremely helpful in aiding the understanding of element associations (Table 1).

6. Each imagery type has characteristics which favor application to certain studies. Researchers can take maximum advantage of resources and increase efficiency by knowing the capabilities of the various imagery types (Tables 4 and 6) and by choosing the imagery appropriate to their needs.
7. Color infrared photography offers the best single choice: recognition ratings of landscape elements remain good despite scale reduction. Color IR is suitable for most needs and is particularly good for vegetation analysis. Effective scales are 1:100,000 or larger with the most useful range being 1:20,000 to 1:60,000.
8. Satellite imagery has low recognition ratings, but is suitable for viewing suspended sediment, river effluent dispersion, and gross landform variation.
9. Relief interpretation from imagery is uncertain, as the recognition ratings indicate. However, clues to relief are given by fragmented patterns of the landscape, drainage dissection, and land-use patterns.
10. In any study, maps and imagery complement each

other: maps provide precise location, place names, and contours, imagery presents water-body characteristics, process features, terrain details and relationships, and accurate vegetational distributions.

GLOSSARY A

Advantages, Disadvantages and Best Uses of Various Imagery

BLACK-AND-WHITE IMAGERY

Black-and-White Panchromatic Photography

Advantages: resolution excellent. Topographic forms, including beach features and beach zones, are fairly easily distinguished. Hydrographic forms appear more clearly and submarine features are visible in greater depths of water than on infrared photography. Vegetation forms are fairly easily distinguished.

Disadvantages: less clear than either infrared or color photography. Tonal range decreases as scale decreases and identification of features is more difficult. Elevation changes are generally not apparent; cliffs are not recognizable without stereoviewer. Scale is usually too large to view regional patterns and large spatial relationships (without splicing); thus drainage patterns, bar systems, river plumes, etc., can be identified but not seen in their spatial perspective.

Best Use: where accurate detailed resolution of small features is required, especially for shoreline features; good for recognition of vegetation types. Recommended scale - 1:20,000 because of tonal range decrease.

Infrared Black-and-White Photography

Advantages: resolution of detail excellent; definition considerably better than on black-and-white panchromatic. Clarity is better than on color prints, but color provides a wider range of tones. Provides extremely good definition of vegetation forms (broadleaf and coniferous types differentiated) and beach features (even to aeolian drift behind dunes). Also has high contrast of wet and dry areas; drainage, shoreline, wetlands, and tide stages are clearly demarcated.

Disadvantages: prints cannot be enlarged and still retain the same resolution and brightness as transparencies. Suspended sediment and submerged deposits are not visible. Wave patterns are not visible (unless sun reflects into camera).

Best Use: studies where high contrast between wet and dry areas is needed or where good discrimination of vegetation types is required. Identification is improved when used in conjunction with black-and-white panchromatic.

Recommended scale - larger than 1:20,000.

COLOR IMAGERY

Color Photography

Advantages: wider range of tone than on black and white which permits easier identification of features at smaller scales than is possible with black and white. Shoreline composition is fairly easily detected, especially at larger scales. Vegetation forms and elevation changes appear clearly; at 1:10,000 and larger, cliffs can be identified without stereographic aid. Suspended sediment appears very clearly and shallow bathymetric variation can usually be discerned. Resolution of detail is excellent; greater on transparencies than on prints.

Disadvantages: coverage for higher latitudes is considerably less than elsewhere. Variations from true color may confuse identification.

Best Use: studies concerned with elevation variation (including cliffs), shoreline composition, sediment suspension, and bathymetric variation. Also good for discrimination of water indicators like vegetation. For topographic variation studies (without aid of stereoviewer).

Recommended scale - 1:12,000 or larger.

Color Infrared Photography

Advantages: combines advantages of wide tonal range of color, sensitivity of detail, and wet/dry contrast of infrared. Vegetation forms appear with greater definition than on color. Drainage channels and land/water interfaces are clearly seen. Soil moisture differences, wetland vegetation types, and high and low water marks are clearly demarcated. Shoreline composition can be interpreted on larger scales. Mangrove shorelines and brackish water marshes show sharp delineation at 1:10,000 and larger. Marsh types are shown clearly.

Disadvantages:

Best Use: for studies requiring differentiation of wetland vegetation forms. Best choice of imagery for general use or when there is only one choice of imagery.

Recommended scale - 1:10,000 or larger depending on use.

ERTS IMAGERY

Earth Resources Technology Satellite imagery provides nonphotographic imagery which is produced through the conversion of electronic signals to photographic negatives.

The images are available as contact prints (1:3,369,000) or as enlargements at 1:1,000,000, 1:500,000, and 1:250,000. The multi-spectral scanner (MSS) is one of two types of ERTS imagery sensors. The MSS sensor produces images at four different wave bands (4,5,6,7). The ERTS imagery was not intended to provide imagery for highly detailed studies or large-scale precision. It is best suited for regional studies involving the distributions and relationships of gross-scaled to medium-scaled features.

ERTS IMAGERY, MSS BANDS

Band 7

Advantages: high contrast wet and dry areas provides sharp delineation of shoreline configuration drainage patterns. Visible elements are presented within spatial perspective. Tidal flats are visible. Marsh/water interfaces and upper wetland boundary are clearly seen. Large plant communities are also seen.

Disadvantages: landscape elements other than those associated with shoreline configuration (bay form, barriers, etc.) nearly impossible to identify.

Differentiation within wetland types is difficult. Of all MSS bands, provides poorest or no view of sediment drift.

Best Use: any studies requiring distinction between wet/dry areas. Studies requiring analysis of regional patterns and gross elements are within their spatial perspective, as drainage patterns, barrier chains, etc.

Recommended scale - 1:250,000

Band 6

Advantages: land/water definition is very clear but not as clear as on Band 7. Shoreline configuration forms (bays, headlands, islands, etc.) are clearly seen. Topographic variations are better distinguished than on Band 7 because of more grey tones; for example, patches of agricultural land and beaches appear. Marsh/water interface and upper wetland boundary are clearly seen.

Disadvantages: because of narrow tonal range, many land features are difficult to interpret. Small features or details are not recognizable or do not appear at all; i.e., resolution is poor except for land/water interfaces. Wetlands appear, but boundaries are fuzzy.

Best Use: studies involving land/water contrast, or land-use practices.

Recommended scale - 1:250,000.

Band 5

Advantages: of all the MSS bands, Band 5 gives the best general image. Sediment patterns are clearly seen, perhaps not as well as on MSS 4 but is not as effected by haze as MSS4. Land features are clearer than on Bands 6 or 7. Vegetated areas are apparent. Bathymetric variation can be seen in shallow water (50-70 feet). Water masses and tidal flats are visible.

Disadvantages: land/water interface clear only where shoreline is sand; other shorelines are fuzzy. Difficult to impossible to interpret relief, tonal definition is poor. Vegetative life-forms cannot be distinguished although vegetated vs. non-vegetated areas are clear. Land/water interface less easily identified than on Band 6.

Best Use: studies concerned with gross topographic features and relationships (mountain ranges, flood plains, etc.); regional patterns of sediment drift can be studied.

Recommended scale - 1:250,000.

Band 4

Advantages: of all the MSS bands, Band 4 gives the best view of topographic forms (when not obscured by atmospheric haze). Relative depth and turbidity of water bodies are fairly clear. Sediment drift is clear. Water masses are seen.

Disadvantages: of all the MSS bands, provides the poorest contrast between land and water: difficult to discern interfaces. Of all the bands, MSS 4 is most effected by atmospheric conditions.

Best Use: studies concerned with regional views of topographic forms and sediment drift.
Recommended scale - 1:250,000

ERTS IMAGERY; COMPOSITE

<u>Color Composite: Bands 4,5, and 7</u>

Advantages: wetland vegetation types fairly easily identified (water-table level is interpretable). Shoreline configuration, associated forms, and drainage patterns are well-defined. Land features are enhanced: clearer than on black-and-white ERTS bands. Large plant communities can be seen.

Disadvantages: resolution poor (poorer than on black and white bands), fuzzy boundaries between vegetative forms and water interfaces. Relief not interpretable. Sediment drift ill-defined, bathymetric variation not shown.

Best Use: studies concerned with regional relationships and patterns of major land forms, shoreline configuration, river mouths, and drainage patterns. Recommended scale - 1:250,000

<u>Satellite Scanning Radiometer, black and white print</u>
(Approximate scale 1:20,000,000 to 1:25,000,000)

Advantages: river mouths and gross outline of large land masses and bodies of water visible. Imagery is thermal, thus, edge of Gulf Stream and approximate location of the continental shelf may be identified. Weather patterns are very clear.

Disadvantages: barrier islands not visible unless wider than about 5 miles. Very narrow tonal range permits recognition only of gross features. Submarine features cannot be seen. Clouds frequently obscure coastline.

Best Use: studies involving weather patterns and their relation to continental position.

GLOSSARY B

Part I: Landscape Elements

Part II: Interface Types

All definitions are from <u>Glossary of Geology</u> American Geological Institute, M. Gary et al. editors, 1972, except where indicated.

LANDSCAPE-ELEMENT TERMS

<u>Relief</u>
- High Relief
- Low Relief
- Coastal Plain

<u>Shore Material</u>
- Rocky
- Skeery (rock)
- Shingle
- Sand, Sandy
- Siltage
- Fringing Reef (coral)
- Barrier Reef (coral)

<u>Topographic Forms</u>
- Coastline
- Promontory
- Cliff
- Truncated Spur
- Barrier
- Alluvial Plain
- Tidal Flat
- Natural Levee
- Dune: stable (veg.)
  - unstable (non-veg.)
- Swash Zone
- Beach
- Beach Crest

<u>Hydrographic Forms</u>
- Bathyorographical variation: great variance
  - little variance (smooth slope)
- Breaker or Breaking Wave: Submarine Bar
  - Shoals
- Channel: Hanging Valley
  - Mouth (river)
  - Inlet
  - Tidal Channel
  - Distributary
  - Drainage Pattern
- Bay: Open Bay or Bight
  - Bayhead Beach
  - Funnel Sea
  - Trough or U-shaped Valley
  - Closed Bay or Lagoon

Site-Specific Features

- Berm
- Beach Ridge
- Overwash Mark
- Spit
- Cusp
- Tidal Delta

Process Features

- Wave Approach
- Water Mass
- River Plume
- Drift (suspended sediment)

Vegetative Life-forms

- Upland Vegetation (moist soils)
  - Wooded
  - Shrubbery
  - Grass
- Wetland Vegetation (wet soils)
  - Wooded Swamp (including special types; i.e., mangrove, nipa palm, cypress, taiga)
  - Shrub Swamp (including special types; i.e., tundra and heath; typically alders, willows, dogwood, buttonbush, swamp-privet)
  - Grass
    - Tidal Marsh
    - Salt Marsh
    - Freshwater Marsh
  - Submerged Aquatic Plants

  - Desert Vegetation (dry soils)

LANDSCAPE-ELEMENT TERMS

Relief

Relief. The vertical difference in elevation between the hilltops or mountain summits and the lowlands or valleys of a given region. A region showing a great variation in elevation has "high relief"; one showing little variation has "low relief."

High Relief. A region showing a great variation in relief has "high relief" (see Relief).

In this project, high relief was defined as relief greater than 100 feet within 4 miles of the coastline.

Low Relief. A region showing little variation in elevation has "low relief" (see Relief).

In this project low relief was defined as relief less than 100 feet within 4 miles of the coastline.

Coastal Plain. Any lowland area bordering a sea or ocean, extending inland to the nearest elevated land and sloping very gently seaward.

Shore Material

Shore Material. The characteristic or dominant compositional substance of the beach. (Author's definition).

Rocky. (a) Any notable, usually bare peak, cliff, promontory, or hill considered as one mass; (b) A rocky mass lying at, near, or projecting above the surface of a body of water.

Skeery. A low, small, rugged and rocky island or reef; an isolated rock detached from the mainland, rising above sea level from a shallow strandflat, and covered by the sea during high tides or stormy weather.

Shingle. Coarse, loose, well-rounded, and waterworn detritus or alluvial material of various sizes; especially beach gravel composed of smooth and spheroidal or flattened fragments relatively free from fine material... Strictly, the term refers to beach pebbles and cobble of roughly the same size; more commonly, it includes any beach material coarser than ordinary gravel.

Sand. A tract or region of sand such as a sandy beach along the seashore, or a desert land.

Sandy. Pertaining to or containing sand or consisting of, abounding in, or covered with sand.

Siltage. A mass of silt.

Fringing Reef. A coral reef that is directly attached to or borders the shore of an island or continent, having a rough, table-like surface that is exposed at low tide; it may be more than 1 km wide, and its seaward edge slopes sharply down to the sea floor. There may be a shallow channel or lagoon between the reef and the mainland, although strictly there is no body of water between the reef and the land upon which it is attached.

Barrier Reef. A long, narrow coral reef roughly parallel to the shore and separated from it at some distance by a lagoon of considerable depth and width.

Topographic Forms

Topographic Form. A landform considered without regard to its origin, cause or history. A landform is defined as any physical recognizable form or feature of the Earth's surface, having a characteristic shape, and produced by natural causes; it includes major forms such as a plain, plateau or mountain, and minor forms such as a hill, valley, slope, esker, or dune.

Coastline. Commonly, the line that forms the boundary between the land and the water, especially the water of a sea or ocean. A general term to describe the appearance or configuration of the land along a coast, especially as viewed from the sea; it includes bays, but crosses narrow inlets and river mouths. --- the terms shoreline and coastline are often used synonymously, but there is a tendency to regard "coastline" as a limit fixed in position for a relatively long time and "shoreline" as a limit constantly moving across the beach.

Promontory. A high, prominent projection or point of land, or cliff of rock, jutting out boldly into a body of water beyond the coastline; a headland.

Cliff. Any high, very steep to perpendicular or overhanging face of rock (sometimes earth or ice) occurring in the mountains or rising above the shore of a lake or river; a precipice. A cliff is usually produced by erosion, less commonly by faulting.

Truncated Spur. A spur that formerly projected into a preglacial valley and that was partially worn away or beveled by a moving glacier that widened and straightened the valley.

Barrier. An elongate offshore ridge or mass usually of sand rising above the high-tide level, generally extending parallel to, and at some distance from, the shore, and built up by the action of waves and currents. Examples include barrier beach and barrier island.

Alluvial Plain. A level or gently sloping tract or slightly undulating land surface produced by extensive deposition of alluvium, usually adjacent to a river that periodically overflows its banks; it may be situated on a flood plain, a delta, or an alluvial fan.

Tidal Flat. An extensive, nearly horizontal, marshy or barren tract of land that is alternately covered and uncovered by the rise and fall of the tide, and consisting of unconsolidated sediment (mostly mud and sand). It may form the top surface of a deltaic deposit. Includes sand flat (predominantly sand) and mudflat (predominantly mud).

Natural Levee. A long, broad, low ridge or embankment of sand and coarse silt, built by a stream on its flood plain and along both banks of its channel, especially in time of flood when water overflowing the normal banks is forced to deposit the coarsest part of its load. It has a gentle slope away from the river and toward the surrounding flood plain, and its highest elevation is closest to the river bank, at or near normal flood level.

Dune. A low mound, ridge, bank, or hill of loose, wind-blown granular material (generally sand, sometimes volcanic ash), either bare or covered with vegetation, capable of movement from place to place but always retaining its own characteristic shape.

Swash Zone. The sloping part of the beach that is alternately covered and uncovered by the uprush of waves and where longshore movement of water occurs in a zigzag (upslope-downslope) manner.

Beach. A gently sloping zone, typically with a concave profile, of unconsolidated material that extends to the place where there is a definite change in material or physiographic form (such as a cliff) or to the line or permanent vegetation (usually of the effective limit of the highest storm waves); a shore of a body of water, formed and washed by waves or tides, usually covered by sandy or pebbly material, and lacking a bare rocky surface.

Beach Crest. A temporary ridge or berm marking the landward limit of normal wave activity.

Hydrographic Forms

Bathyorographical. Pertaining to the description of the ocean floor.

Breaker. A sea-surface wave that has become too steep so that the crest outraces the body of the wave and collapses into a turbulent mass on shore or over a reef or rock. Syn. Breaking Wave.

Submarine Bar. A longshore bar that is always submerged, or never exposed above the water level even by low tides. (A longshore bar is defined as a low, elongate sand ridge, built chiefly by wave action, occurring at some distance from, and extending generally parallel with, the shoreline, being submerged at least by high tides, and typically separated from the beach by an intervening trough).

Shoal. An elevation, or an area of such elevations at a depth of 10 fathoms or less, composed of material other than rock or coral. It may be exposed at low water.

Channel. The hollow bed where a natural body of surface water flows or may flow; a natural passageway, or depression of perceptible extent containing continuously or periodically flowing water, or forming a connecting link between two bodies of water, a watercourse.

Hanging Valley. A coastal valley whose lower end is notably higher than the shore to which it leads, produced where betrunking or rapid cliff recession causes the mouths of streams to "hang" along the cliff front.

Mouth. The place of discharge of a body of water into a larger body of water, as where a tributary enters the main stream or where a river enters a sea or lake.

Inlet. A short, narrow waterway running between islands or connecting a bay, lagoon, or similar body of water with a larger body of water, such as a sea or lake; e.g. a waterway through a coastal obstruction (as a reef or barrier island) leading to a bay or lagoon.

Tidal Channel. A major channel followed by the tidal currents, extending from offshore well into a tidal marsh or tidal flat.

Distributary. An irregular, divergent stream flowing away from the main stream and not returning to it, as in a delta or on an alluvial plain.

Drainage Pattern. The configuration or arrangement in plan view of the natural stream courses in an area. It is related to local geologic and geomorphic features and history.

Bay. A large tract of water that penetrates into the land and around which the land forms a broad curve. By international agreement, a bay is a water body having a baymouth less than 24 nautical miles wide and an area that is equal to or greater than the area of a semicircle whose diameter is equal to the width of the baymouth.

Open Bay. An indentation between two capes or headlands, so broad and open that waves coming directly into it are nearly as high near its center as on adjacent parts of the open sea; a bight.

Bight. A long, gradual bend or gentle curve, or slight, crescent-shaped indentation, in the shoreline of an open coast or of a bay; it may be larger than a bay, or it may be a segment of a feature smaller than a bay. A tract of water or a large bay formed by a bight: an Open Bay.

Bayhead Beach. A small crescentic beach formed at the head of a bay by materials eroded from adjacent headlands and carried to the bayhead by longshore currents and/or storm waves.

Funnel Sea. A gulf or bay that is narrow at its head and wide at its mouth and that deepens rapidly from head to mouth, thus resembling one half of a funnel split lengthwise.

Trough. Any long and narrow depression in the Earth's surface, such as one between hills or with no surface outlet for drainage; especially a broad, elongated, U-shaped valley, such as a glacial trough or a trench.

U-shaped Valley. A valley having a pronounced parabolic cross profile suggesting the form of a broad letter "U", with steep parallel walls and a broad nearly flat floor;..

Closed Bay. A bay indirectly connected with the sea through a narrow pass.

Lagoon. A shallow stretch of seawater such as a sound, channel, bay, or salt-water lake, near or communicating with the sea and partly or completely separated from it by a low, narrow, elongate strip of land, such as a reef, barrier island, sandbank, or spit; especially the sheet of water between an offshore coral reef and the mainland. It often extends roughly parallel to the coast, and it may be stagnant.

Site-Specific Features

Berm. A low, impermanent, nearly horizontal or landward sloping beach, shelf, ledge, or narrow terrace on the backshore of a beach, formed of material thrown up and deposited by storm waves; it is generally bounded on one side or the other by a beach ridge or beach scarp.

Beach Ridge. A low, essentially continuous mound of beach-and-dune material (sand, gravel, shingle) heaped up by the action of waves and currents on the backshore of a beach beyond the present limit of storm waves or the reach of ordinary tides, and occurring singly as one of a series of approximately parallel deposits. The ridges are roughly parallel to the shoreline and represent successive positions of an advancing shoreline.

Overwash Mark. A narrow, tongue-like ridge of sand formed by overwash on the landward side of a berm.

Spit. A small point or low tongue or narrow embankment of land commonly consisting of sand or gravel deposited by longshore drifting and having one end attached to the mainland and the other terminating in open water, usually the sea; a finger-like extension of the beach.

Cusp. Any of a series of low, crescent-shaped mounds or ridges of beach material built by wave action and separated by smoothly curved shallow depressions spaced at more or less regular intervals along and generally at right angles to the shoreline, and varying in length across their seaward-pointing apices from less than a meter to many kilometers; a beach cusp, a storm cusp, a giant cusp, a cuspate spit, and a cuspate foreland.

Tidal Delta. A delta formed at the mouth of a tidal inlet on both the seaward and lagoon sides of a barrier island or baymouth bar by changing tidal currents that sweep sand in and out of the inlet.

Vegetative Life-forms

Life Form. The vegetative form of an organism such as tree, shrub, annual, liana, bunchgrass, broad-leafed sclerophyll, etc. Synonymous with growth form. (Cain, p. 483).

Moist Soils. Usually not saturated with water but for long periods have enough moisture for plant growth. (U.S. Department of the Interior, p. 87).

Wooded. Covered with trees. (Webster's New Collegiate Dictionary).

Shrubbery. A growth of shrubs; shrubs collectively. Shrub is defined as a low, usually several-stemmed woody plant; a bush. (Webster's New Collegiate Dictionary).

Grass. Grass-covered ground. (Webster's New Collegiate Dictionary).

Wetland. Lowlands covered with shallow and sometimes temporary or intermittent waters. (Fish and Wildlife Service).

Wet Soils. Seasonally or permanently saturated with water. (U.S. Department of the Interior, p. 87).

Swamp. A water saturated area, intermittently or permanently covered with water, having shrub- and tree-type vegetation.

Tidal Marsh. A low, flat marsh bordering a coast (as in a shallow lagoon or a sheltered bay), formed of mud and of resistant mat of roots of salt-tolerant plants, and regularly inundated during high tides.

Salt Marsh. Flat, poorly drained land that is subject to periodic or occasional overflow by salt water, containing water that is brackish to strongly saline, and usually covered with a thick mat of grassy halophytic plants; e.g. a coastal marsh periodically flooded by the sea.

Freshwater Marsh. A marsh that depends on nontidal freshwater rather than a saltwater source. Along the southeastern Atlantic coast of the United States the term savannah is used for marshy alluvial flats with occasional clumps of trees.

Submerged Aquatic Plant. A hydrophyte the main part of which grows below the surface of the water.

Desert. An area of low moisture due to low rainfall, i.e. less than ten inches annually, high evaporation, or extreme cold and which supports only specialized vegetation, not that typical of the latitudes, and is generally unsuitable for human habitation under natural conditions.

Dry Soils. Lack moisture for plant growth for long periods. (U.S. Department of the Interior, p. 87).

INTERFACE-TYPE TERMS

Sand Beach: A straight or gently curving broad beach of sandy material formed on the mainland and possessing many of the characteristics of a barrier-chain coast except the lagoon. (Author's definition).

Barrier Island: A long, low, narrow, wave-built sandy island representing a broadened barrier beach that is sufficiently above high tide and parallel to the shore, and that commonly has dunes, vegetated zones, and swampy terranes extending lagoonward from the beach. Also, a long series of barrier beaches as a barrier chain (a series of barrier islands, barrier spits, and barrier beaches extending along a coast a considerable distance).

Barrier Beach: A single narrow, elongate sand ridge rising slightly above the high-tide level and extending generally parallel with the shore, but separated from it by a lagoon or marsh; it is extended by longshore drifting and is rarely more than several kilometers long.

Sand Beach with Rock Headlands: A narrow beach formed in an Open Bay or Bight between rocky cliffed headlands, commonly broadly crescentic in plan and concave toward the sea; or a series of such beaches. (Author's definition).

Pocket Beach. A small narrow beach formed in a pocket (an enclosed or sheltered place along a coast such as a reentrant between rocky cliffed headlands or a bight on a lee shore), commonly crescentic in plan and concave toward the sea, and generally displaying well-sorted sands; a Bayhead Beach; or a series of such beaches.

Shingle Beach. A narrow beach, usually the first to form on a coastline having resistant bedrock and cliffs, composed of shingle, and commonly having a very steep slope on both its landward and seaward sides.

Rock Coast. A jagged rocky coastline, especially where dangerous to shipping.

Delta Shoreline. A prograding shoreline produced by the advancing of a delta into a lake or sea.

Delta: the low, nearly flat, alluvial tract of land deposited at or near the mouth of a river, commonly forming a triangular or fan-shaped plain of considerable area enclosed and crossed by many distributaries of the main river, perhaps extending beyond the general trend of the coast, and resulting from the accumulation in a wider body of water of sediment supplied by a river in such quantities that it is not removed by tides, waves, and currents. Most deltas are partly subaerial and partly below water.

Estuary. (a) The seaward end or the widened funnel-shaped tidal mouth of a river valley where freshwater mixes with and measurably dilutes seawater and where tidal effects are evident; e.g. a tidal river, or a partially enclosed coastal body of water where the tide meets the current of a stream: (b) a portion of the ocean, as a firth or an arm of the sea, affected by freshwater; (c) a drowned river mouth formed by the subsidence of land near the coast or by the drowning of the lower portion of a nonglaciated valley due to the rise of sea level.

Fjord Coast. A deeply indented, glaciated coast characterized by a partial submergence of glacial troughs, and by the presence of steep parallel walls, truncated spurs, and hanging valleys.

Coral-reef Shoreline. A shoreline formed by deposits of coral and algae, partly exposed at low tide, and characterized by reefs built upward from a submarine floor or outward from the margin of a land area.

Mangrove Coast. A tropical or subtropical low-energy coast the shoreline of which is overgorwn by mangrove vegetation, such as in southern Florida.

Open-coast Marsh or Mudflat. Open-coast Marsh: a salt marsh formed along an open coast (a coast exposed to the full action of waves and currents). A coastal marsh is defined as a marsh bordering a seacoast, generally formed under the protection of a barrier beach, or enclosed in the sheltered part of an estuary.

Mudflat Coastline: a mudflat formed along an open coast, a relatively flat foreshore composed of fine silt. (Author's definition).

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13. ABSTRACT

This final report summarizes the products of more than four years of research in the classification of coastal environments and includes three manuscripts detailing the results and conclusions of three studies not issued in technical report form. The three studies included are titled "Coastal Wave Climates of the Americas," "Coastal Marine Fauna and Marine Climates of the Americas," and "An Assessment of Remote Sensing as a Tool in Classifying Coastal Landscape Elements."

In addition, an evaluation of data quality, quantity, availability, and suitability for the purposes of classifying coastal environments is included. Also contained within this report are statements as to the kinds of expertise required to accomplish the research conducted and the expertise generated during the investigation.

We have concluded that the coastal environment may adequately be classified into a series of natural environmental complexes which recur in disparate geographical locations when the dominant processes shaping the environment are similar in quality and magnitude and that within these complexes assumptions of homogeneity of environmental attributes are appropriate at the analysis scales used. It is proposed that the natural complexes of the coastal environment could serve as geographic units in future information systems for the coastal environments.

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14. KEY WORDS	LINK A		LINK B		LINK C	
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Coastal Coastal Classification Coastal Environments Coastal Wave Climates Coastal Marine Fauna Coastal Marine Climates Remote Sensing Coastal Landscape Elements Information Systems						

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